Non-foveal text processing and fixation positions in reading

White, Sarah Jane

Non-foveal Text Processing and Fixation Positions in Reading

Sarah Jane White

Thesis submitted for the Degree of Doctor of Philosophy

University of Durham, Department of Psychology

2003

Sarah Jane White

Non-foveal Text Processing and Fixation Positions in Reading

PhD, 2003

Abstract

This thesis reports seven experiments which investigate what determines where the eyes move during reading. Specifically, the experiments examine what kinds of linguistic information can influence where words are first fixated and refixated. Experiment 1 showed that fixations landed nearer to the beginning of words in which the initial letter sequence was misspelled, compared to when the words were spelled correctly. Experiments 2 and 3 showed that the effects of misspellings on saccade programming can not be explained by lexical non-foveal preprocessing, and therefore the results of Experiment 1 must be due to preprocessing of the orthographic familiarity of word initial letter sequences. These results were confirmed in Experiment 4, which showed that first fixations landed nearer to the beginning of correctly spelled words with orthographically irregular, compared to orthographically regular, initial letter sequences. Furthermore, Experiment 5 showed that these effects held for sentences presented in upper case text. Furthermore, Experiments 6 and 7 demonstrated that the influence of orthography on saccade programming was independent of foveal processing difficulty. These results are most consistent with an attraction based explanation in which preprocessing of orthography, independent of processing load, influences the word length and launch site based saccade programme to produce a small shift in the preferred viewing position in the direction of the orthographic irregularity. The results also show that linguistic processing can influence the direction and length of refixation saccades. Furthermore, although preprocessing of orthography can influence saccade programming, the results provide no consistent evidence for an influence of orthography on prior fixation durations or probabilities. These results indicate that there is independent processing of when and where the eyes move. The absence of robust "parafoveal-on-foveal" effects provides no support for parallel processing models of reading.

Declaration

I hereby declare that this thesis has been composed by myself and that the research reported herein has been conducted by myself.

July, 2003

Sarah J. White

Experiments 1 and 3 are reported in:
White, S.J., & Liversedge, S.P. (in press). Orthographic Familiarity Influences Initial Eye Fixation Positions in Reading. *European Journal of Cognitive Psychology.*

Experiments 4 and 5 have been submitted in the following manuscript:
White, S.J., & Liversedge, S.P. (submitted). Orthographic Regularity Influences the Eyes' Landing Positions in Reading.

Statement of Copyright

Acknowledgements

Many thanks to my supervisor, Simon Liversedge, who helped make the research process exciting, challenging, rewarding and most of all a lot of fun. I am also very grateful to Dorine Vergilino-Perez, Keith Rayner and John Findlay for providing valuable help, advice and support. Also thanks to other members of the Centre for Vision and Visual Cognition who have given lots of useful advice and encouragement.

Thanks also to everyone in the University of Massachusetts Eye Movement Laboratory who helped provide a wonderfully stimulating and exciting research environment. Special thanks to Charles Clifton, Barbara Juhasz, Jane Ashby and Tessa Warren for helping to teach me how to use the saccade contingent change software.

I am also grateful to Peter Roy for writing the computer programmes to generate letter sequence frequencies. Many thanks also go to many other people in the Psychology Department at Durham for their help and support. Finally, a big thank you to everyone who participated in the experiments.

Table of Contents

List of Tables

List of Illustrations

Chapter 1

General Introduction

As we read each line of text, our eyes make a series of pauses and fast movements (Javal, 1879, cited in Huey, 1908). The fast movements are known as saccades and the pauses between them as fixations. During each pause of the eyes, text in the centre of vision, and further away from fixation, is processed at a number of different levels. For example, visual, orthographic, and lexical characteristics might be processed. Text away from the centre of vision is processed for three purposes. First, preprocessing of text facilitates language processing when it is subsequently fixated, as shown by shorter fixations on the preprocessed words. Secondly, preprocessing of text allows selection of the next word target, for example, whether to fixate or skip the following word. Thirdly, preprocessing of text enables programming of the next eye movement towards the selected word target. This thesis is primarily concerned with the latter, that is, examining what kinds of preprocessed information can be used to influence where words are fixated when we read. Such preprocessing of text away from the point of fixation is based on visually degraded information.

Eye movements are essential to reading because only a small amount of text can be processed in high quality vision at any one time. For each pause of the eyes, acuity is very good in the central area of vision where visual information falls on to the area of the retina called the fovea. Foveal vision is generally thought to be within the central two degrees of fixation, which generally equates to three to four characters in any one direction from fixation. However there is a gradual reduction in acuity from the fovea to the periphery. (Rayner, 1998). Words that are presented within foveal vision are identified more quickly than words presented further from fixation (Rayner & Morrison, 1981) and it is very difficult to read using only non-foveal vision (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). Consequently we move our eyes in order to read more than a few words of text efficiently. Importantly, because on average saccades extend seven to nine character spaces (Rayner, 1998), the saccade target will generally be outside the area of foveal vision. Consequently the site of the saccade target must be preprocessed on the basis of visually degraded information.

Despite the visual limitations on preprocessing of text, the size of saccades is generally determined by textual rather than visual factors. Landolt (1891) (cited in Huey, 1908) and Huey (1908) reported that the number of eye pauses is more closely related to the number of words than the actual size of the text. More recently, studies have shown that even if the size of the text is changed, saccades still extend over the same average number of letters (Morrison, 1983, Morrison & Rayner, 1981; O'Regan, 1983; O'Regan, Lévy-Schoen, & Jacobs, 1983). Therefore reports of where the eyes move in reading are generally based on textual features such as which words or characters are fixated. Throughout this thesis, "word n" denotes the word being fixated, "word n-1" is the word to the left of the fixated word and "word n+1" is the word to the right of the fixated word.

Although this thesis is primarily concerned with where words are fixated, this Chapter will first provide a more general introduction to the kinds of information that can be preprocessed away from fixation and how this can be used to influence where the eyes move when we read. For a more complete review of eye movements in reading see Rayner (1998). Section 1.1 will first review to what extent, and what characteristics of, non-fixated text can be preprocessed as shown by general measures of eye movements in reading. It will be emphasised that the factors that determine when and where the eyes move can be quite different, hence some types of preprocessed information might influence when, but not where, the eyes move. Section 1.2 will review the factors which influence whether words are fixated, and whether words are fixated more than once before leaving them. Section 1.3 will present the evidence for what determines where words are first fixated and Section 1.4 will discuss what determines where words are refixated. Each of the latter three sections will also review to what extent models of eye movements in reading can account for the evidence. Many of these models generally focus on when, rather than where, the eyes move in reading but this thesis will concentrate only on what determines where the eyes move. Finally, in order for non-foveal information to influence saccade programming, it must be processed during the previous fixation. Consequently it is possible that processing of the same information might also influence the duration or pattern of fixations before the critical non-foveal text is fixated. The evidence for such "parafoveal-on-foveal effects" will be reviewed in Section 1.5. Overall, it will be shown that the existing evidence for orthographic influences on where words are first fixated, and for parafoveal-on-foveal effects, is limited and inconsistent. The final Section (1.6) of this Chapter will outline how these issues will be addressed within the structure of this thesis.

1.1: Preprocessing of Non-fixated Text

In order to consider what determines where the eyes move in reading we must first examine to what extent, and what kind of, information can be preprocessed in non-foveal vision. Landolt (1891) (cited in Huey, 1908) compared the number of fixations made with the number of words read to estimate that 1.55 words must be read for each pause of the eyes. Huey (1908) used a tachistoscopic technique to manipulate the amount of text available for each brief presentation of text. On average, ten letter spaces could be read for each exposure. More recent studies have examined more accurately and in much more detail how much and what kinds of information can be extracted from text away from the centre of fixation.

Section 1.1.1 will discuss research that has investigated how much and what type of information can be extracted during a single fixation. However, the amount of text that can be processed is not the same for every fixation and Section 1.1.2 will review how this changes with the difficulty of the text. Section 1.1.3 will discuss a range of studies which have investigated in more detail what kinds of information can be extracted from word n+1. These studies have investigated how text is preprocessed by examining how foveal processing of these words is facilitated as a result of the preview that was available before they were fixated. Section 1.1.4 will explain that the types of non-foveal information that can be preprocessed and subsequently influence when the eyes move, may not necessarily be the same as the types of non-foveal information that can influence where the eyes move.

1.1.1: The region and type of text that can be processed on each fixation

The area and type of text that can be processed on each fixation is called the perceptual span and has been investigated using the moving window technique (McConkie & Rayner, 1975; Rayner, 1975b). The technique involves changing text beyond particular distances from the dynamic fixation point. Using this technique, the perceptual span is measured by the area or type of text that must be presented within the window around fixation in order that there is no difference in eye movement reading measures between conditions with and without the moving window. McConkie and Rayner showed that in English readers the perceptual span extends up to fifteen characters to the right of fixation (see also: Rayner, 1986; Rayner & Bertera, 1979; Rayner et al., 1981). Rayner, Well and Pollatsek (1980) established that the perceptual span to the left of fixation extends as far as the beginning of the fixated word up to a maximum of three to four characters (see also: McConkie & Rayner, 1976a; but see Binder, Pollatsek, & Rayner, 1999). Importantly, the span is asymmetric with more processing in the direction of text that has not yet been fixated, hence the opposite pattern is found for languages read in the opposite direction (Pollatsek, Bolozky, Well, & Rayner, 1981).

The type of information that can be processed within the perceptual span is also relative to the position of the fixation, with word length information being extracted further from fixation than letter information (Ikeda & Saida, 1978; McConkie & Rayner, 1975; Rayner, 1986). Furthermore, the size of the perceptual span varies with different languages (Inhoff & Liu, 1998; Ikeda & Saida, 1978; Osaka, 1987, Osaka, 1993), perhaps because of differences in the density of information in these languages. The fact that the perceptual span is smaller when there is more information to process within a given area of text suggests that the processing difficulty of text might influence the size of the perceptual span.

1.1.2: Text difficulty limits non-foveal processing

The variation in the size of the perceptual span with different languages indicates that it is the difficulty of text, rather than acuity, which regulates the extent or depth of processing in non-foveal vision. Dearborn (1906) showed that slow readers produce more fixations and he inferred from this that “The slow readers have a narrower span or working extent of attention” (cited in Huey, 1908, p.178.). Erdmann and Dodge (1898) (cited in Huey, 1908), Buswell (1937) and Landolt (1891) (cited in Huey, 1908) also showed that more difficult text required more fixations. Jacobson and Dodwell (1979) reported that readers made shorter saccades, more regressions and longer fixation durations for normal text compared to sequences of letter strings not requiring sentence comprehension. However, reading measures alone are not a clear indication of the extent of non-foveal processing because saccades may not simply be directed to the far edge of the preprocessed region. Nevertheless, studies using the moving window technique have supported these early assumptions showing that beginner readers have smaller perceptual spans than skilled readers (Rayner, 1986) and perceptual spans are smaller for text that is difficult to read (Inhoff, Pollatsek, Posner, & Rayner, 1989; Rayner, 1986). These results suggest that when both foveal and non-foveal processing are difficult, non-foveal processing is reduced. However experiments that have measured preview benefit have shown that foveal and non-foveal processing difficulty can independently influence non-foveal processing.

Preview benefit is the reduction in reading time on a word as a result of previous preprocessing of that word. Preview benefit is measured experimentally using the boundary saccade contingent change technique, as shown in Figure 1.1. Typically, longer reading times are produced on the critical word when the preview is incorrect (e.g. *kplnmrsxv*) compared to when it is correct (e.g. *technique*) and the difference in reading times between these conditions is known as preview benefit. (Rayner & Pollatsek, 1989).

```
…the boundary kplnmrsxv shows…
        *
…the boundary technique shows…
                     *
```

Figure 1.1. Example of the boundary saccade contingent change technique. The fixation location is shown by an asterisk. The invisible boundary is located at the very end of the word "boundary". When the saccade crosses the boundary the following word changes. The first line shows the sentence presented before the change and the second line shows the sentence presented after the change. Therefore the preview before the change is never directly fixated.

Experiments using the boundary technique have found smaller preview benefits when the non-foveal word is difficult to process due to word frequency (Inhoff & Rayner, 1986) or unpredictability (Balota, Pollatsek, & Rayner, 1985). Similarly, other studies have shown that foveal difficulty reduces preview benefit on the following word (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999). Hence both foveal and non-foveal processing difficulty reduce non-foveal processing. However it is currently unclear whether it is the extent and/or type of non-foveal processing that is reduced. Nevertheless, experiments have been undertaken to investigate more closely what kinds of information can be preprocessed from the following word.

1.1.3: Orthographic and phonological processing of word n+1

A number of studies have used the boundary contingent change technique to measure preview benefit in order to examine what kind of information can be extracted from non-foveal text and used on the following fixation. McConkie and Rayner (1976b) suggested that non-foveal information is stored in a "visual buffer" and then integrated with foveal information on the next fixation. However Rayner, McConkie, & Ehrlich (1978) showed facilitation from preview when the saccade was simulated such that the preview was presented in non-foveal vision and the target was then presented in foveal vision whilst the participants maintained fixation. That is, the information from the preview and target were integrated without information about the difference in the position of the stimuli on the retina, which might usually be provided by the eye movement between them. A visual buffer would need such information about distance in order to align the two stimuli. The visual buffer was also criticised by McConkie and Zola (1979) and Rayner, McConkie, and Zola (1980) who showed that subjects could read text in alternate case, which changed (e.g. CaSe to cAsE) with each saccade, without any disruption to their eye movements. Such a manipulation would have caused severe disruption to a visual buffer and it was concluded that information must be integrated across saccades in an abstract form. Such abstract preprocessing is predominantly for the initial letters of the following word. Studies using isolated words with boundary contingent changes (Balota & Rayner, 1983; McClelland & O'Regan, 1981; Rayner et al., 1978; Rayner, McConkie et al., 1980) and sentences with the moving window technique (Inhoff, 1989b; Rayner, Well, Pollatsek, & Bertera, 1982) have shown that the initial three letters of words provide almost as much preview benefit as when the entire word is available for preview. Note that although non-foveal processing of word length also facilitates preview benefit, this does not interact with non-foveal orthographic information in order to constrain the number of potential word candidates (Inhoff, Radach, Eiter, & Juhasz, 2003). The preprocessed information might be used to facilitate subsequent processing or allow attention to be directed to unprocessed text (Rayner, McConkie et al., 1980). Other studies have suggested that phonological information can be processed from non-foveal text and used to facilitate processing on subsequent fixations (Henderson, Dixon, Peterson, Twilley, & Ferreira, 1995; Liu, Inhoff, Ye, & Wu, 2002; Pollatsek, Lesch, Morris, & Rayner, 1992; Pollatsek, Tan, & Rayner, 2000). However morphological (Lima, 1987; Inhoff, 1989a; but see Deutsch, Frost, Pollatsek, & Rayner, 2000), purely lexical (Lima & Inhoff, 1985) and semantic (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Balota & Rayner, 1991; Inhoff, 1982; Inhoff & Rayner, 1980; Rayner, Balota, & Pollatsek, 1986) non-foveal information do not appear to be integrated across saccades when those words are subsequently fixated.

To summarise, studies of the perceptual span show that, in English, text up to 15 characters to the right of fixation can be processed in non-foveal vision. Abstract orthographic and phonological information, especially from word initial letters, can be integrated across saccades to facilitate later processing. However the amount of non-foveal processing is limited by foveal and non-foveal processing difficulty. The studies presented in this section have largely used reading time measures as a measure of non-foveal processing. However quite different types of non-foveal information might influence when and where the eyes move.

1.1.4: Independent processing of when and where the eyes move

Evidence from a range of very different experiments suggests that the factors which influence when and where the eyes move are quite different. Studies using simple visual tasks have shown that the triggering of saccades is independent of the length of saccades (Becker & Jürgens, 1979) and some models of eye movement programming consider these two factors to be quite separate (Findlay & Walker, 1999). In support of this, studies based on corpora of eye movement reading data have found no relationship between fixation durations and subsequent saccade lengths (Andriessen & de Voogd, 1973; Kliegl, Olson, & Davidson, 1983; McConkie & Zola, 1984; Radach & Heller, 2000; Rayner & McConkie, 1976). However, because corpus studies do not use controlled stimuli there is a large amount of variability in the results and consequently any relatively small relationships between fixation durations and saccade lengths may have been overlooked. There is some evidence to suggest that long fixation durations can lead to longer subsequent saccade lengths at localised positions in controlled sentences (Inhoff, Topolski, & Wang, 1992). Nevertheless, there is additional evidence to suggest that when and where the eyes move is processed largely independently. Rayner and Pollatsek (1981) showed that delaying the onset of text largely influenced when, but not where, the eyes moved whereas varying the size of the moving window largely influenced where, but not when, the eyes moved. Consequently, Rayner and Pollatsek argued that the types of information used to influence when and where the eyes move are independent.

In summary, the preview benefit studies discussed in Section 1.1.3 use measures of when the eyes move to show that orthographic and phonological information can be extracted from non-foveal text. However, the evidence presented in this Section indicates that quite different types of information might influence when and where the eyes move. Therefore it is quite possible that the information that is extracted from non-foveal text to influence where the eyes move might be quite different to that discussed in Section 1.1.3. Consequently it is important to examine exactly what kinds of information can be preprocessed and used to influence where the eyes move. In addition, the factors that determine which words are fixated might be quite different to those that influence where words are fixated. The following Section (1.2) will review what determines where the eyes move in relation to which word is fixated and the issue of what determines where words are first fixated will then be considered in Section 1.3.

1.2: What Determines Which Words are Fixated

As we read we must decide whether to refixate the current word, fixate the next word, skip one or more words to the right of fixation, or move the eyes to an earlier point in the text. The decision to move the eyes back to text that has already been read is not generally included in models of eye movements in reading. The issue of which particular words are targeted when such regressive eye movements are made will not be considered here. Instead, this section is primarily concerned with how processing of the characteristics of words on the first reading of text influences whether they are fixated. Section 1.2.1 explains how the characteristics of particular words influence skipping and refixation probabilities. Section 1.2.2 reviews the models of eye movements in reading which account for which words are fixated largely in terms of visual processing of text. Section 1.2.3 reviews the models which also use linguistic processing of text to explain which words are fixated. Note that many models of eye movements in reading have focused, in some cases almost exclusively (e.g. Just & Carpenter, 1980; Thibadeau, Just, & Carpenter, 1982; Yang & McConkie, 2001), on when, but not where the eyes move. However only the models that make predictions about which words are fixated will be considered here. Section 1.2.4 summarises what the different models predict about which words are fixated and evaluates to what extent these accounts explain the data presented in Section 1.2.1.

1.2.1: Factors influencing skipping and refixation probabilities

Both visual and linguistic factors influence the probability of fixating or skipping words. Short words are more likely to be skipped (Blanchard, Pollatsek, & Rayner, 1989; Brysbaert & Vitu, 1998; Rayner, 1979; Rayner & McConkie, 1976), perhaps because they are closer to fixation in less degraded vision. Linguistic factors also influence which words are skipped (O'Regan, 1979; Gautier, O'Regan, Le Gargasson, 2000). Words that are predictable within the context of the sentence are more likely to be skipped (Altarriba, Kroll, Sholl, & Rayner, 1996; Balota et al., 1985; Binder et al., 1999; Ehrlich & Rayner, 1981; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner & Well, 1996; Schustack, Ehrlich, & Rayner, 1987; but see Hyönä, 1993a) and high frequency words are also more likely to be skipped than low frequency words (Radach & Kempe, 1993; Rayner & Fischer, 1996; Rayner, Sereno, & Raney, 1996). Brysbaert and Vitu showed that word length is a much better predictor of word skipping than either word frequency or contextual constraint. Furthermore, although the linguistic characteristics of words influence the probability of word skipping, this does not mean that words must be properly identified before they are skipped. Experiments using boundary saccade contingent change have shown that words can be skipped even when the preview was a nonsense letter string (Blanchard et al., 1989). Such cases show that although some kind of lexical identification stage may have been reached before these words were skipped, this certainly was not achieved on the basis of the actual information available.

Factors similar to those that influence word skipping also influence the probability of making additional fixations on words before leaving them (refixations). Acuity limitations certainly influence the probability of refixating a word, long words are more likely to be refixated than short words (Vitu, O'Regan, & Mittau, 1990). Refixations also occur if the initial fixation is not optimal for processing the entire word, for example if part of the word is too visually degraded to be processed from the initial fixation position (O'Regan & Lévy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). Consequently, the probability of refixating a word increases as the initial fixation location is further from the middle (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989). Words that are difficult to process due to linguistic factors such as infrequency (Inhoff & Rayner, 1986; Rayner et al., 1996) or unpredictability (Balota et al., 1985) are also more likely to be refixated. Therefore both visual and linguistic factors influence the probability of refixating the fixated word and skipping non-foveal words.

1.2.2: Explanations: Visual influences on which words to fixate

The models that explain word skipping largely in terms of visual processing of text are generally referred to as oculomotor accounts. Early oculomotor accounts (Bouma & de Voogd, 1974; Huey, 1908; Kolers, 1976) were based on the notion that eye movement patterns were influenced only by the general difficulty of the text rather than by specific characteristics of particular words. For example, a general shortening of saccade lengths would reduce the proportion of words that were skipped and increase the proportion of words that were refixated. More recently, O'Regan (1990) proposed the strategy-tactics theory which suggests that a scanning strategy based on visuo-motor control with rescue tactics can best explain eye movements in reading. Words are skipped when riskier reading strategies are adopted and refixations are made when the position of the initial fixation is not optimal (away from the word centre). O'Regan's account might predict that short words are more likely to be skipped and long words more likely to be refixated. Reilly and O'Regan (1998) compared computer simulations of different saccade targeting strategies. They concluded that the best strategy is to simply target the longest word within a window of text to the right of fixation, unless the current fixation duration is very short, in which case a saccade is made to the next word to the right.

1.2.3: Explanations: Linguistic influences on which words to fixate

In contrast to the oculomotor accounts, Hochberg (1975, 1976) suggested that "cognitive search guidance" (expectations about the text) influence which words are fixated in reading. More recent linguistic processing based accounts can be divided into three general categories, serial attention shift models, accounts involving independent processing of when and where the eyes move, and ideal observer explanations. The serial attention shift accounts were the first models to provide very comprehensive and mechanistic explanations of what determines which words are fixated. Furthermore, the notion of saccades following attention, or any sort of spatially localised processing activity, is an important concept that will be discussed again in Section 1.3.3. Therefore the background to these accounts and the models themselves will be described in some detail.

A number of visual perception studies have suggested that saccades follow shifts of attention (Rizzolatti, Riggio, Dascola, & Umiltá, 1987; Deubel & Schneider, 1996, Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser 1995; Shepherd, Findlay, & Hockey, 1986; but see Stelmach, Campsall, & Herdman, 1997). Dearborn (1906, cited in Huey, 1908) also suggested that attention moves ahead of each fixation, pulling the eyes along to follow it. Similarly, McConkie (1979) suggested that saccades move to attended non-foveal regions of text where visual acuity is degraded. Attention could be allocated in a localised manner, for example, to particular words, allowing saccades to be directed to specific word targets. However attention must be localised within words if this explanation is also to explain why words are refixated. It has been suggested that attention could be allocated over a distributed attentional gradient and saccades could be directed to the region of greatest attention regardless of word boundaries (Clark, 1999; Inhoff, Radach, Starr, & Greenberg, 2000; LaBerge & Brown, 1989). However, the most detailed serial attention shift accounts are based on the notion that attention is localised equally to one word at a time.

In Morrison's (1984) serial attention shift account, attention moves to the following word when processing of the previous word is accomplished. When attention shifts to the following word an eye movement program is planned to this word and is executed after the necessary programming time is complete. Morrison's model does not account for whether the current word is refixated, but it does suggest a mechanism for word skipping. If processing of word n+1 is completed then attention shifts to word n+2. If attention has shifted to word n+2 before the eye movement to word n+1 has reached a critical stage of programming, then the eye movement to word n+1 is cancelled and an eye movement to word n+2 is programmed. Crucially, attention shifting to word n+2 before the critical stage of the eye movement programme to word n+1, depends on the speed at which word n+1 can be processed in non-foveal vision. As the processing speed of word n+1 is related to linguistic processes, this means that Morrison's model predicts that words that are easier to process, such as high frequency predictable words, are more likely to be skipped than words that are difficult to process, such as low frequency unpredictable words.

The E-Z reader model (Rayner, Reichle, & Pollatsek, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, in press) is based on Morrison's account with the crucial distinction that the serial shifts of attention are decoupled from programming and execution of eye movements. For each word, a critical stage of processing (L_1) initiates planning of a saccade to the following word and, similar to Morrison's model, the eye movement is executed after the necessary programming time is complete. The time at which L_1 is completed is related to factors such as the visibility of words, word frequency or word predictability. Once processing of the attended word is complete (L_2) attention shifts to the following word. If L_1 is reached on word n+1 whilst the eye movement programme to word n+1 is still in a labile stage, then the eye movement can be re-programmed to word n+2. Importantly though, similar to Morrison's account, because word skipping is related to the speed at which the skipped words are processed (time to complete L_1), skipping probabilities are influenced by the length and linguistic characteristics of words.

The E-Z reader model also accounts for why words are refixated. Whether a refixation saccade is programmed depends on the length of the word being fixated, hence longer words are more likely to be refixated. If the first stage of word processing (L_1) is completed during the labile refixation saccade programme then the refixation saccade is cancelled, otherwise it is executed. The time to complete L_1

depends not only on linguistic factors but also on the visibility of the letters within the word. Therefore if the initial fixation is away from the word centre (reducing visibility of the whole word), or if words are difficult to process, then refixations are more likely.

Therefore, both Morrison's (1984) model and E-Z reader explain why visual (word length) and linguistic characteristics of words influence the probability of word skipping and E-Z reader also explains how these factors influence the probability of refixating words. Other serial attention shift based accounts also suggest that the ease of word processing influences the probability of word skipping, however the precise mechanisms are specified in much less detail.

Suppes' (1990, 1994) stochastic minimal control model makes a similar suggestion to Morrison in that non-fixated words are skipped if processing of them is complete in non-foveal vision. Reilly's (1993) attention shift model is also similar to that of Morrison except that attention is allocated to multiple words in parallel. In addition to ease of processing influencing skipping probabilities, Reilly's model also predicts that short words will be more likely to be skipped simply because they are more likely to be processed in parallel within the spotlight of attention. Neither Suppes' nor Reilly's models provide clear accounts about the nature of refixations. A different approach was taken by Salvucci (2001) who developed a general model of eye movements called "EMMA" based on the principles of E-Z reader. EMMA is not sensitive to context and so does not produce more skipping of predictable words. However, because attended objects are encoded at a speed related to frequency, the model does predict that high frequency words are more likely to be skipped than low frequency words.

In contrast to the serial attention shift accounts, recently a number of models have been proposed in which processing of when and where to move the eyes is quite independent. Similar to Findlay and Walker's (1999) account, Reilly and Radach's (2003) Glenmore model triggers saccades when activation in the saliency map (where system) exceeds that in the fixate centre (when system), at which point saccades are targeted to the point of maximum salience in the saliency map. Activity in the fixate centre is influenced by a linguistic processing module and activity generally falls over time. The saliency map codes for the presence or absence of letters and it is limited by eccentricity. Such visual influences on activation in the salience map explain why word length influences which words are fixated, long words have greater salience and so are more likely to be fixated. The saliency map also receives activation from the linguistic processing module which provides equal levels of activation (related to the linguistic processing of each word) to each letter of those words. Words that are difficult to process accumulate more activation. Therefore words that are easy to process are more likely to be skipped and the currently fixated word is more likely to be refixated if it is difficult to process.

The Saccade-generation With Inhibition by Foveal Targets (SWIFT) model, proposed by Engbert, Longtin and Kliegl (2002; see also Engbert & Kliegl, 2001), is also based on independent processing of when and where to move the eyes. Similar to the E-Z reader model, there are two stages of linguistic processing. In the first stage lexical activity increases and in the second stage processing is completed and lexical activity reduces. The level of activity influences the probability of a word being selected as the saccade target. The time at which saccade programming is initiated is influenced by inhibition from fixated words which is related to linguistic processing. However attention, or language processing, can be distributed across multiple words and processing of these words is limited by eccentricity. Saccades are directed to the next word within the attentional gradient which has not been completely lexically processed, that is, words with high lexical activity. Hence words that are short or easy to process tend to be processed more quickly, are more likely to have low levels of lexical activity, and are therefore less likely to be refixated and more likely to be skipped.

The accounts discussed so far in this section are largely word based in that lexical processing is considered to be equal within each word and saccades are directed to particular word targets. In contrast, the Mr. Chips model (Legge, Klitz, & Tjan, 1997; Legge, Hooven, Klitz, Mansfield, & Tjan, 2002) is an ideal observer model of reading which assumes that the fovea is simply directed to the best location to help disambiguate the identity of the next unrecognised word, regardless of word boundaries. The model uses knowledge about lexical candidate sets to calculate the probability of recognising a word on the basis of available information. Short words are more likely to have a sufficiently informative section of the word within the range of vision but outside Mr. Chips' fovea. Consequently short words are more likely to be able to be identified without being brought into the fovea, that is, short words are more likely to be skipped. Although it seems likely that skipping and refixation probabilities would be influenced by lexical factors, the authors make no specific predictions about how factors like word frequency and word predictability might influence which words are fixated.

To summarise, a number of detailed models have been developed which predict that linguistic and visual factors influence which words to fixate. Most of the accounts limit processing by eccentricity, hence short words are easier to process because more of the word is available in high quality vision, and consequently short words are more likely to be skipped and less likely to be refixated. In general, the serial attention shift accounts and SWIFT incorporate critical language processing stages. If the critical stage is not completed for the fixated word then it is refixated, and if it is completed for a non-fixated word then this word is skipped. Hence skipping and refixation probabilities are influenced by linguistic factors. In contrast, the Glenmore model suggests that saccade targets are selected on the basis of competition between alternative word targets, which is influenced by linguistic processing. However not all models (e.g. Mr. Chips) make clear predictions about which words are fixated.

1.2.4: Summary: What determines which words are fixated

To summarise, the evidence reviewed in Section 1.2.1 clearly shows that both visual and linguistic processing influences which words are fixated (refixation and skipping probabilities). However, not all of the models of eye movements in reading are able to explain these results. The early accounts of eye movements in reading generally did not predict that specific characteristics of text would directly influence where the eyes moved (Bouma & de Voogd, 1974; Huey, 1908; Kolers, 1976). Oculomotor accounts (O'Regan, 1990) suggest that the probability of skipping and refixating words depends on the position of a fixation, word boundaries and reading strategies. These accounts demonstrate that the principal characteristics of eye movements in reading can be explained on the basis of visual processing of text. However these accounts can not explain the results of studies showing influences of linguistic processing on which words are fixated. In contrast, serial attention shift accounts (Morrison, 1984, Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press; Reilly, 1993; Suppes, 1990, 1994) suggest that word frequency and predictability can influence the probability of word skipping and the E-Z reader model also suggests that these factors influence refixation probabilities. Recent models based on independent processing of when and where the eyes move (Engbert & Kliegl, 2001; Engbert et al., 2002; Reilly & Radach, 2003) also predict that both visual and linguistic factors influence which words are fixated.

Section 1.2 has shown that complex linguistic processing of foveal and non-foveal text can influence where the eyes move in reading. Explanations of linguistic influences on what determines which words are fixated include saccades being directed to the locus of attention or some sort of spatially localised processing activity (Morrison, 1984; Engbert & Kliegl, 2001; Engbert et al., 2002; Reilly & Radach, 2003). Alternatively, as in the E-Z reader model (Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press), completion of processing produces a saccade programme to the following word which becomes the saccade target, even though it may not have been attended before the saccade is executed. Section 1.3 will review what determines where words are first fixated and Section 1.4 will review what determines where words are refixated. Explanations for linguistic influences on where words are fixated are similar to the former category above, that is, saccades are directed to the locus of attention or other localised processing activity. The important difference between these accounts is that the models reviewed in this section localise attention or processing activity to particular words, and saccades are therefore targeted on a word by word basis. In contrast, the accounts that will be discussed in the next two sections use much more localised attention or processing activity in order to target saccades to particular locations within words. These two types of influences are quite different, the former produces discrete changes in the saccade target and the latter might produce graded influences on fixation positions. Furthermore, the types of word based processing associated with discrete shifts of attention (or localised processing activity) might be quite different to the types of within word based processing associated with graded differences in the localisation of attention (or processing activity).

1.3: What Determines Where Words are First Fixated

Section 1.1.3 explained that orthographic and phonological information can be extracted from non-foveal text and used to facilitate processing when that text is subsequently fixated. Section 1.2.1 demonstrated that visual factors such as word length and linguistic factors such as word frequency and predictability can be extracted from non-foveal text and used to influence whether words are subsequently skipped or fixated. Section 1.3.1 will show that much more simple non-foveal information is preprocessed and used to influence where words are first fixated. Section 1.3.2 will review accounts which suggest that only processing of visual and oculomotor factors influence where words are first fixated. Section 1.3.3 will review explanations which suggest that non-foveal preprocessing of the linguistic characteristics within words also influence where words are first fixated. As indicated in Section 1.2.4, such linguistic processing accounts are generally based on the notion of saccades being directed to the locus of attention or other measure of processing load. Section 1.3.4 summarises the factors that influence where words are fixated and evaluates the extent to which the different explanations account for these effects.

1.3.1: Factors influencing where words are first fixated

There is a lot of evidence to suggest that non-foveal preprocessing of word length, and oculomotor variables such as launch site and prior fixation duration, broadly explain where words are first fixated. In line with this, fixation positions in normal reading are very similar to those for sequences of meaningless letter strings (Vitu, O'Regan, Inhoff, & Topolski, 1995). This Section will begin by discussing how these visual and oculomotor factors influence fixation positions. Studies will then be presented which provide evidence for and against the possibility that more complex non-foveal processing can also influence where words are first fixated. It should be noted that all of the experiments discussed below, and those in this thesis, examine fixation positions for just one eye. These studies assume, in line with Hering's Law (Hering, 1868, cited in Bassou, Pugh, & Granié, 1993) that the two eyes are generally fixating at the same location. It should be noted that recent research has suggested that this is not always the case (Bassou et al., 1993; Cornelissen, Munro, Fowler, & Stein, 1993; Heller & Radach, 1995, 1999; Hendriks, 1996; Radach, Heller, Wiebories, & Jaschinski, 1996; Ygge & Jacobson, 1994). These studies suggest that recording only monocular eye position with binocular vision does not necessarily give a true reflection of "fixation position" because the other eye could be fixating on a different location. However the studies presented below, and in this thesis, assume that even if the two eyes have slightly different fixation positions, they should still both be influenced by the factors being investigated.

There is a lot of evidence to suggest that non-foveal preprocessing of word length is important in influencing where words are first fixated. McConkie, Kerr, Reddix, and Zola (1988) suggested that saccades are targeted to the word centre, although fixations may not land at the word centre due to oculomotor factors. Saccades might be targeted to the word centre because this could be the best position from which to process the word. Experiments using isolated words have shown that this is generally the optimal viewing position to produce the shortest word recognition times (O'Regan & Jacobs, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan et al., 1984). However similar experiments have shown that the optimal viewing position is influenced by the sub-lexical characteristics of the word (Deutsch & Rayner, 1999; Farid & Grainger, 1996; Grainger, O'Regan, Jacobs & Segui, 1992; Hyöna, Niemi & Underwood, 1989; Kajii, & Osaka, 2000; O'Regan et al., 1984). Nevertheless, it makes sense that the optimal viewing position should generally be in the word centre because this would allow the largest possible area of the word to be processed in foveal vision. A number of studies using natural reading have shown that the probability of refixating words is higher when the initial fixation is further away from the word centre (McConkie et al., 1989; Radach & McConkie, 1998; Rayner & Fischer, 1996; Rayner et al., 1996; Vitu, 1991c; Vitu et al., 1990). However, in contrast to isolated word recognition studies, reading experiments have found much smaller (Vitu, 1991c; Vitu et al., 1990), opposite (O'Regan, Vitu, Radach, & Kerr, 1994; Radach & Heller, 2000; Vitu, McConkie, Kerr, & O'Regan, 2001) or no (Rayner & Fischer, 1996; Rayner et al., 1996) optimal viewing position effects on fixation durations.

In fact, instead of landing at the centre of the word, first fixations are most likely to land on the preferred viewing position (Rayner, 1979), which is between the beginning and the middle of words (Deutsch & Rayner, 1999; Dunn-Rankin, 1978; McConkie et al., 1988; McConkie et al., 1989; McConkie & Zola, 1984; O'Regan, 1981; Radach & Kempe, 1993; Rayner et al., 1996; Rayner, Fischer, & Pollatsek, 1998; Vitu, 1991a, 1991b, 1991c; Vitu et al., 1995, Vitu et al., 1990). The preferred viewing position shows that fixation positions systematically vary with word length which indicates that the length of words is an important variable in saccade targeting.

Possible visual, oculomotor and linguistic explanations for the preferred viewing position phenomenon will be discussed in Sections 1.3.2 and 1.3.3. Word length also influences the mean initial landing positions on words (Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner et al., 1996). However Vitu (1991b) showed that initial fixation positions were the same on nine and 13 letter words, hence initial fixations are nearer the word beginning rather than just left of centre for longer words.

The spaces between words are essential visual cues used to calculate word length and influence saccade programming. McConkie and Rayner (1975) showed that saccades were shorter when space information was eliminated using the moving window technique (see also O'Regan, 1979; O'Regan, 1980). Experiments have been reported arguing that reading is no different in unspaced text compared to when spaces are preserved (Epelboim, Booth, & Steinman, 1994, 1996; Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997). However, Rayner, Fischer et al. (1998) found that unspaced text produced first fixation landing positions nearer to the beginning of words, indicating that the spaces do influence where words are first fixated. Furthermore, Pollatsek and Rayner (1982) showed that the presence of spaces was most important for defining word boundaries, saccade lengths were still reduced even when non-linguistic space fillers were used. In addition, Tsai and McConkie (2003) showed no effects of word length on fixation positions for Chinese text in which words are not delimited by spaces. Morris, Rayner and Pollatsek (1990) found that space information affects landing position if it is presented at any time during fixation. Therefore word units, demarked by the visual cues provided by spaces, are clearly important in guiding landing positions.

Although most fixations land on the preferred viewing position, there is substantial variability in the distribution of landing positions on words. McConkie et al. (1988) suggested that saccades launched from distant positions tend to undershoot the word centre and saccades launched from near positions tend to overshoot the word centre. McConkie et al. suggested that these systematic effects might be explained by range error (Kapoula, 1985; Kapoula & Robinson, 1986). Many studies have now shown the systematic relation between launch and landing positions such that saccades launched from further away land nearer to the beginning of words (Hyönä, 1995; McConkie, Kerr, & Dyre, 1994; McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie, 1998, Rayner et al., 1996; but see Vitu, 1991a). Radach and McConkie demonstrated that the effect of launch site on initial fixation positions is much larger than that of word length. Radach and McConkie reported that for every one character increase in word length, the mean fixation position is approximately 0.15 characters further into the word (though see Rayner, et al., 1996, for larger mean differences), whereas for every one character reduction in launch site, the mean fixation position is 0.35 characters further into the word. Nevertheless, the location of the previous fixation and non-foveal preprocessing of word length are the most important factors in determining where words are first fixated.

In addition, McConkie et al. (1988) reported that saccades are targeted more accurately to the word centre when the prior fixation duration is longer. Findlay (1981a) and Coëffé and O'Regan (1987) reported similar results in non-reading tasks. McConkie et al. (1988) found that for long fixation durations prior to fixating words five to eight characters in length, undershooting from far launch sites and overshooting from near launch sites was reduced such that mean landing positions were more accurately targeted to the left of the word centre (the preferred viewing position). McConkie et al. (1994) claimed to find a similar pattern of results. Similarly, Beauvillain and Doré (1995) showed that, in an artificial task in which all saccades were launched from near launch sites, overshooting was reduced for long prior fixation durations such that more fixations landed on the preferred viewing position. However Radach and Heller (2000) failed to find a relationship between prior fixation duration and saccade accuracy in a study of corpus reading data (see also Radach & McConkie, 1998).

In addition to all these factors, McConkie et al. (1988) showed that when launch site and word length were held constant the landing position distributions were normally distributed, which the authors attributed to random oculomotor error. Furthermore, longer saccades produced more variable landing positions. Radach and Kempe (1993) and Radach and McConkie (1998) also showed that the fixation pattern on the word before the critical word can influence initial fixation positions on the critical word. The authors showed that if launch site was held constant, landing positions were further into the word when the previous word had been refixated compared to if it was skipped. These differences could be due to differences in preview. That is, greater preprocessing of word n might enable saccades to be directed further into it (as suggested by Rayner & Morris, 1992; Rayner et al., 1996). There might be greater opportunity for preprocessing of word n when the previous fixation was a refixation on word n-1 compared to if word n-1 was skipped. If the previous word was skipped then preprocessing may have focused on identifying the skipped word (word n-1) rather than preprocessing the following word (word n). In addition, Radach & McConkie showed that the position of the word in the line of text also influences initial fixation positions, fixations at the beginning of a line land further into words and fixations on words at the end of a line land nearer to the beginning.

To summarise, there is considerable evidence to suggest that word length, launch site and random error are important factors in influencing where words are first fixated. Prior fixation duration and saccade lengths might also influence saccade targeting accuracy. However, there is other evidence which suggests that more complex preprocessing of the characteristics of words can also influence where they are first fixated. Studies suggesting that lexical preprocessing of words can influence initial fixation positions will be reviewed next, followed by more recent studies examining whether orthographic preprocessing can influence landing positions. These studies will be discussed in some detail because they directly relate to the hypotheses that will be tested later in this thesis.

The first studies to investigate whether preprocessing of lexical information influences landing positions examined whether the distribution of informativeness (the importance of letter sequences for word recognition) within words could influence where words are initially fixated (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood, Clews, & Everatt, 1990; Underwood, Hyönä, & Niemi, 1987). Informativeness was defined by participants' ability to guess words on the basis of the word initial or final letters, or by dictionary counts of the number of words containing particular letter sequences. Underwood and colleagues generally showed that initial fixations land nearer to the beginning of words with informative beginnings like "skateboard" and nearer to the end of words with informative endings like "underbelly". Hyönä et al. suggested that informative regions of words might attract fixations as a result of semantic preprocessing. However, as noted in Section 1.1.3, there is considerable evidence to suggest that semantic information can not be processed in non-foveal vision (Altarriba et al., 2001; Balota & Rayner, 1991; Inhoff, 1982; Inhoff & Rayner, 1980; Rayner et al., 1986). Underwood, Hyönä et al. suggest that saccades might be attracted to informative locations and Underwood, Clews et al. suggest that saccades might be attracted to locations where words are not readily identified (parafoveal guidance). However Hyönä (1993b, 1995) argued that these studies confounded the variable of informativeness with orthographic, morphological and semantic variables (see also: Everatt, Bradshaw, & Hibbard, 1998). Furthermore, Rayner and Morris (1992) failed to replicate Underwood et al.'s findings and neither Underwood, Bloomfield and Clews (1989), Hyönä (1995) nor Beauvillain, Doré and Baudouin (1996) found any effect of the distribution of informativeness on initial fixation positions. It is clear that lexical informativeness either has no effect on first fixation landing position or the effect is weak and difficult to replicate.

Later studies investigated whether other types of lexical preprocessing might influence fixation positions. There is some evidence for an influence of morphology on initial fixation positions (Deutsch & Rayner, 1999; Inhoff, Brühl, & Schwartz, 1996; Hyönä & Pollatsek, 1998; but see Andrews, Miller, & Rayner, in press; Beauvillain, 1996; Radach, Inhoff, & Heller, in press), no evidence for an effect of word frequency (Rayner et al., 1996) and mixed evidence for an influence of context (Lavigne, Vitu, & d'Ydewalle, 2000; but see Everatt & Underwood, 1992; Rayner et al., 2001; Vonk, Radach, & van Rijn, 2000). Other studies have suggested that syntactic processing (Frazier & Rayner, 1982) and clause wrap up can influence the length of subsequent saccades (Hill & Murray, 2000; Rayner, 1975a; Rayner, Kambe, & Duffy, 2000) but these effects are driven by foveal, rather than non-foveal processing issues.

To summarise, although many studies have investigated whether non-foveal lexical processing can influence initial fixation positions, there are a number of conflicting results and possible confounds. However, these studies do not preclude the possibility that non-foveal preprocessing beyond the level of word length but less complex than lexical processing can influence where words are first fixated. A number of experiments suggest that non-foveal preprocessing of letter information can influence fixation positions. Such studies have shown that factors such as removal of non-foveal letter information (Inhoff, 1989b; Morris et al., 1990; Rayner et al., 1982), presentation of only partially correct previews (Inhoff, 1990), or the presence of nonsense letter strings in sentences (McConkie, Underwood, Zola, & Wolverton, 1985) can shorten saccade lengths. However, the differences in saccade length in these studies could have arisen from differences in refixation or skipping probabilities, or even from changes in eye movement strategies over a series of fixations. Consequently it is difficult to conclude whether these studies show that letter information influences where the eyes move once a word target has been selected or whether they just reflect selection of which word to fixate. Zola (1984) argued that orthography can influence saccades into words on the basis that saccade lengths were shorter into words in which the first, fourth and last letters were misspelled compared to a correctly spelled condition. However it is not clear whether the misspellings also influenced fixation positions on words or whether there were any differences in the familiarity of the initial letter sequences between the correct and misspelled conditions.

More recently, studies have specifically investigated whether non-foveal letter information influences where words are first fixated by comparing eye landing positions on words with frequent and infrequent initial letter sequences. It is important to understand that although these experiments have focused on the effects of non-foveal preprocessing on landing positions, differences in landing positions must always be explained by either differences in saccade length, differences in launch site, or both differences in saccade length and launch site. This is a basic, but very important point that has not been fully addressed by studies reporting differences in fixation positions in the literature. Therefore, before the studies investigating the effects of orthography on fixation positions are described, the possible relationships between fixation positions, saccade lengths and launch sites will be outlined.

For example, if there is a mean difference in landing position of, say 0.4 characters, this might be explained in three possible ways. First, the effect may be accounted for by a difference in saccade length such that one condition might produce saccades 0.4 characters shorter than another. In such a situation the condition with shorter saccades would land 0.4 characters nearer the word beginning than the condition with longer saccades. This first possibility is illustrated in Figure 1.2.

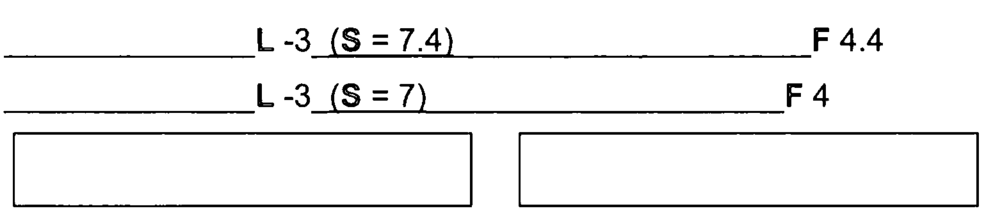

Figure 1.2 A 0.4 character difference in fixation position (F), accounted for by a 0.4 character difference in saccade length (S) where launch site (L) is constant.

Secondly, the landing position effect might be explained by a difference in launch site such that in one condition launch sites may be 0.4 characters further away from the beginning of the critical word than in another condition. Such a difference may be due to the range effect whereby launch sites influence fixation positions such that saccades which are launched from further away produce fixations nearer the word beginning (McConkie et al., 1988). This second possibility is illustrated in Figure 1.3.

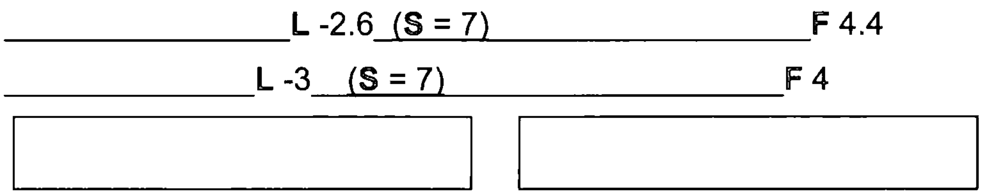

Figure 1.3 A 0.4 character difference in fixation position (F), accounted for by a 0.4 character difference in launch site (L) where saccade length (S) is constant.

Thirdly, both saccade length and launch site might together produce a difference in landing position. For example, saccades might be 0.2 characters shorter and launched from 0.2 characters further away in one condition compared to another. The net result would be a 0.4 character difference in landing position. This third possibility is illustrated in Figure 1.4.

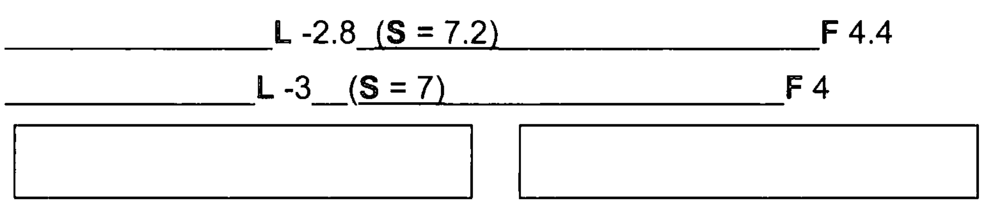

Figure 1.4 A 0.4 character difference in fixation position (F), accounted for by a 0.2 character difference in launch site (L) and a 0.2 character difference in saccade length (S).

In order for the characteristics of a word to influence the launch site, the word characteristics must have been processed on the fixation before the launch site fixation. Alternatively, the characteristics of a word might influence the decision of which word to fixate. For example, whilst fixating word n-2, the characteristics of word n might attract saccades such that the decision is taken to fixate word n, rather than word n-1 on the following fixation. Similarly, whilst fixating word n-1, the characteristics of word n might attract saccades such that the decision is taken to fixate word n, rather than making another fixation on word n-1. That is, the characteristics of a word might have an effect on the launch site by influencing the probability of skipping or refixating previous words. The latter possibility is illustrated in Figure 1.5. Section 1.3.3 will explain how such differences might arise.

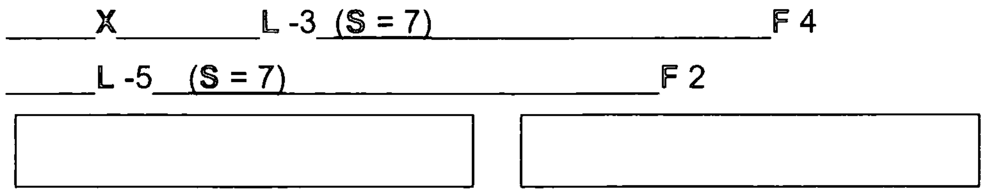

Figure 1.5 A two character difference in fixation position (F), accounted for by a two character difference in launch site (L) where saccade length (S) is constant. Note that in the first case, two fixations are made on the first word (X and L) whereas in the second case the first word is fixated only once (L).

Importantly though, the relationship between saccade lengths, launch sites and fixation positions is not quite as simple as represented above for at least two reasons. First, the mean fixation positions are based on a distribution of landing positions which in turn are influenced by a different distribution of launch sites. Secondly, the relationship between differences in launch sites and differences in fixation positions is not necessarily linear. As explained earlier in this Section, it has been suggested that differences in launch site produce differences in fixation positions as a result of under and over shooting the word centre, that is, due to range error (McConkie et al., 1988). Radach and McConkie (1998) calculated that a difference of 0.35 characters in landing position might be explained by a launch site difference of one character. Therefore the mean difference in launch site might be larger than the impact this actually has on the mean difference in fixation position. For example, a mean difference in fixation position of 0.4 characters might be explained by a mean difference in saccade lengths of 0.3 characters (which accounts for 0.3 characters of the fixation position difference) and a mean difference in launch site of 0.3 characters (which accounts for 0.1 characters of the fixation position difference).

To summarise, both differences in saccade lengths and differences in launch positions might contribute to differences in landing position. A number of studies will now be described which have examined whether the orthographic characteristics of words can be preprocessed and influence where they are fixated. These experiments have largely focused on differences in fixation positions, rather than the differences in saccade lengths and launch sites that underlie these effects. A summary of these findings is presented in Table 1.1. The table demonstrates that most previous studies have not fully reported differences in saccade length or launch site. In contrast, the present thesis includes comprehensive analyses of saccade lengths and launch sites for every difference shown in fixation position.

Table 1.1 *Mean Initial Landing Positions, Saccade Lengths and Launch Sites for Words with Infrequent or Frequent Initial Letter Sequences in Studies of Reading. Where Necessary the Means are Collapsed Across Other Variables Such as Context or Morphology. * Indicates p < .05. - Indicates not Specified by Authors.*

Experiment type	Author	Language	Condition	Landing position	Saccade length	Launch site
Single sentence	Hyönä (1995)	Finnish	Infrequent	3.07	8.16	-
			Frequent	3.37	8.16	-
			Difference	0.3*	0	-
	Radach et al. (in press)	German	Infrequent	3.40	8.40	5.55
			Medium	3.53	8.68	5.7
			Frequent	3.71	8.79	5.62
			Difference	0.31*	0.39*	0.07
Two sentences	Liversedge and Underwood (1998)	English (Exp 1)	Infrequent	4.85	-	-
			Frequent	4.79	-	-
			Difference	-0.06	-	-
		English (Exp 2)	Infrequent	4.1	-	-
			Frequent	4.01	-	-
			Difference	-0.09	-	-
	Vonk et al. (2000)	Dutch	Infrequent	4.24	-	-
			Frequent	4.49	-	-
			Difference	0.25*	-	-
Corpus	Radach and Kempe (1993)	German	Infrequent	2.95	9.6	-
			Frequent	2.99	9.7	-
			Difference	0.04	0.1	-

Hyönä (1995) presented words in sentences with orthographically regular or very irregular word beginnings. The irregular words included letters that rarely occur in Finnish. Hyönä found that fixations landed nearer to the beginning of the orthographically irregular words, especially on the space before the word. Similar effects of orthographic familiarity (the sum of the frequencies of words containing a particular letter sequence) on initial fixation positions have been found in sentence reading in Dutch (Vonk et al., 2000) and German (Radach et al., in press).

Vonk et al. (2000) presented eight to ten letter long Dutch compound words with relatively frequent and infrequent word initial letter sequences embedded in short passages (two lines) of text. Skim readers were excluded from the analyses and regression analyses were undertaken instead of analyses across items. Vonk et al. showed that for both near and far launch sites, fixations landed nearer to the beginning of words with infrequent than frequent initial letter sequences. Radach et al. (in press) presented eight to ten letter long German compound words with low, medium or high frequency initial letter sequences embedded in single line sentences. Similar to Vonk et al., Radach et al. showed that fixations landed nearer to the beginning of more irregular beginning words regardless of launch site. Radach et al. also showed a graded effect such that fixations landed nearer the word beginning for words with low compared to medium, and medium compared to high, frequency word initial letter sequences.

In Hyönä's (1995) study, the irregular word beginnings included very infrequent letters. Vonk et al. (2000) and Radach et al. (in press) do not specify whether individual letter frequency was controlled in their experiments. Therefore, although these three studies suggest that orthographic familiarity can influence initial fixation positions on words, it is unclear whether this is due to preprocessing of individual letters or letter sequences. Furthermore, it is unclear whether the effects might be due to visual or linguistic preprocessing of text. For example, Inhoff, Starr, and Shindler (2000) showed that shorter saccades were made to words presented in upper case embedded within a sentence otherwise presented entirely in lower case, compared to if the critical word was also presented in lower case. Furthermore, Kajii, Nazir and Osaka (2001) showed that, in Japanese, the visually more complex kanji characters were more likely to be fixated than the visually less complex kana characters. Therefore cues such as visual distinctiveness might influence where words are first fixated. It is unclear whether preprocessing of visual distinctiveness or familiarity might have mediated the effects reported by Hyönä, Vonk et al. and Radach et al. or whether these effects were due to linguistic processing of orthography.

Other studies of fixation positions during reading have shown no effects of orthography. Analyses of a corpus of German reading data showed no effect of orthography on word initial fixation positions (Radach & Kempe, 1993; Radach & McConkie, 1998). However these studies have been criticised for not using strong manipulations of orthographic regularity (Hyöna, 1995). Furthermore, Vonk et al. (2000) suggest that corpus studies might have failed to find landing position effects because they induce a "risky" reading strategy compared to the careful reading strategy induced by single sentence reading.

All of the studies presented so far investigating the effects of orthography on landing positions have used languages other than English. Liversedge and Underwood (1998) reported no main effects of orthography on initial fixation positions in a study using English sentences. Underwood et al. (1988) misspelled the third letter of words but found no effect of misspellings on fixation positions. Therefore, there is certainly no strong evidence that orthography influences where words are first fixated in the reading of English. Note that the role of orthography on fixation positions might vary with different languages. It is possible that, in contrast to a language like Finnish, English may not have sufficiently infrequent individual letters or letter sequences to produce an effect of orthography on fixation positions, that is, there may be a ceiling effect (see Appelman & Mayzner, 1981).

Other experiments have examined the effect of orthography on fixation positions on letter strings in artificial tasks. Typically, participants successively fixate two or three letter strings presented adjacently and then make some form of categorical decision on the basis of the strings they have fixated. These experiments provide a greater degree of control over the location from which saccades are launched. Advocates of such tasks usually argue that they are intended to generalise to reading, although clearly the tasks do not demand sentence comprehension, or even in some cases, word recognition processes. Experiments using such techniques in French have shown that word initial infrequent letter sequences produce first fixation landing positions nearer the beginning of words than words with frequent initial letter sequences (Beauvillain & Doré, 1998; Beauvillain et al., 1996; Doré & Beauvillain, 1997). These effects have been shown to hold for saccades to nonwords, suggesting that the effects are sub-lexical, and saccades to words in upper case text, suggesting that the effects are independent of specific lower case letter features. However studies of artificial tasks in German and English have failed to show orthographic landing position effects (Kennedy, 1998, 2000b; Radach, Krummenacher, Heller, & Hofmeister, 1995).

Also note that the effect of orthography on fixation positions is likely to be isolated to the first few letters of words due to acuity or processing limitations. Beauvillain and Doré (1998) found an effect of orthographic regularity on landing position when the first, but not the second, bigram was illegal. Underwood et al. (1988) also found no effect of misspellings on landing positions when the third letter of the word was misspelled. Both these studies suggest that there is a limit to the extent that parafoveal orthographic processing influences landing positions.

To summarise, there is a lot of evidence to show that visual and oculomotor factors can largely explain what determines where words are first fixated. There is some evidence to suggest that lexical preprocessing of words might influence fixation positions, but there are a notable number of studies that have disputed these effects. Nevertheless, some studies have suggested that orthographic preprocessing can influence landing positions. Sentence reading studies in Finnish, German and Dutch have shown that orthographically irregular beginning words produce fixations nearer the word beginning than orthographically regular beginning words. However, it is unclear to what extent these results might be explained by preprocessing of individual letters, rather than letter sequences. Similar effects have been found using artificial tasks in French. Although a number of other studies have failed to show such orthographic influences on fixation positions, it is unclear whether this might be due to the use of insufficiently strong manipulations of orthography, differences between languages, or that the effect of orthography on fixation positions is simply not robust. Section 1.3.2 will review visual and oculomotor explanations of initial fixation positions and Section 1.3.3 will review accounts which suggest that preprocessing of linguistic characteristics within words can also influence where words are first fixated.

1.3.2: Explanations: Visual influences on where words are first fixated

A number of accounts have been proposed to explain why most fixations land on the preferred viewing position. The principal visual explanation is based on the finding that fixations land at the "centre of gravity" of a stimulus configuration (Coren & Hoenig, 1972). Findlay (1981b; 1982) called this the "global effect", he found that saccades directed to two targets land between the two stimuli but closer to the launch site. Coëffé and O'Regan (1987) and Vitu (1991b) suggested that saccades might land just left of the centre of words due to the fact that the centre of gravity calculation might be based on a cortical representation which is transformed by the cortical magnification factor (Rovamo & Virsu, 1979). The portion of the target nearer fixation will have greater cortical representation and so may have greater weight in the centre of gravity calculation, consequently producing fixations just left of centre rather than on the geometric centre of the target. It is also possible that the global effect might be influenced by the presence of multiple word objects rather than just the target word, although it is unclear what effect the presence of other targets may have. Alternatively, the eyes might tend to land just left of the word centre for oculomotor reasons. More saccades might be launched from distant than near launch sites, hence, in line with the range effect (Kapoula, 1985; Kapoula & Robinson, 1986) more saccades might undershoot than overshoot the word centre. Another possibility is that refixations are sometimes programmed before words are fixated (Vergilino & Beauvillain, 2000, 2001). For these cases initial fixations might land nearer the word beginning, hence the preferred viewing position is nearer the word centre for single fixation cases. However, at least in normal reading, it has so far not been possible to distinguish between those cases in which fixations land near the word beginning because of preprogramming, and those cases in which fixations land near the word beginning due to oculomotor error. Despite the wide range of possible explanations, it is clear that the preferred viewing position phenomenon might be explained entirely by visual, or perhaps oculomotor, factors.

In fact, most models of eye movements in reading do not provide a mechanistic account of how visual or oculomotor processes might influence fixation positions. Most models simply state which factors are involved, and other accounts simply choose not to explain this issue (Reilly, 1993; Engbert & Kliegl, 2001; Engbert et al., 2002; Morrison, 1984; Just & Carpenter, 1980; Reichle et al., 1998; Thibadeau et al., 1982; Yang & McConkie, 2001). In contrast to the explanations of which words to fixate (Sections 1.2.2 and 1.2.3), the models are generally much more unanimous in claiming that visual and oculomotor processes are the only factors which determine where words are first fixated.

O'Regan's (1990) strategy-tactics theory predicts that saccades are targeted to the middle or just left of the middle of words (the optimal viewing position) using information from word boundaries (spaces). Suppes (1990) suggests that saccades are directed to the centre of words. McConkie et al. (1988) suggested that saccades are targeted to the word centre but this calculation is influenced by systematic range error, random error and prior fixation duration. A number of models have largely incorporated McConkie et al.'s suggestions in order to account for saccade programming to words once the word target has been selected (Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003). McConkie et al. (1994) developed mathematical accounts of these factors. Models of eye movements generally also provide quite simple accounts of where words are fixated. Salvucci (2001) suggested that once a saccade target has been selected, the final position is influenced by random error. The model does not predict the systematic error due to launch site reported by McConkie et al. (1988) and consequently it does not predict landing position distributions on words like those found in reading. General models of eye movements include mechanisms that might explain some aspects of saccade targeting in reading. Clark's (1999) attention based salience map account explains phenomena such as the global effect and effects of prior fixation duration on saccade targeting accuracy. However it is not clear how launch site might influence the allocation of attention or saccade targets. Findlay and Walker's (1999) account also directs saccades to the point of highest activation within a salience map. The model might explain the effects of the perceptual span on saccade programming by "spatial selection" and it might explain targeting of the word centre by global effect mechanisms. However, similar to Clark's account, it is unclear if or how the model might account for influences of launch site or linguistic preprocessing on saccade targeting.

To summarise, various visual or oculomotor based explanations have been provided to explain the preferred viewing position phenomenon and it is clear that these variables alone might be responsible for the effect. Most models of eye movements in reading explain fixation positions in words using either some or all of the suggestions made by McConkie et al. (1988). Namely, saccades are targeted to words on the basis of word length information with systematic range error and random oculomotor error. However, these accounts can not explain the results of the studies described in Section 1.3.1 suggesting that orthographic information can influence fixation positions within words. As explained above, the results of Inhoff, Starr et al. (2000) and Kajii et al. (2001) indicate that visual distinctiveness or familiarity might also influence fixation positions. Therefore it is possible that the effects of orthography on fixation positions might be explained by such basic visual processes.

Reichle et al. (in press) suggest that low spatial frequency information, such as the presence of spaces between words as well as ascenders and descenders in lower case text, might be used to guide saccade programming to a selected word target. Such low spatial frequency processing would be completed within an early visual processing stage that enables selection of the next word target. However Reichle et al. do not stipulate exactly what influence low spatial frequency features such as ascenders would have on saccade programming. Therefore it is not at all clear if or how Reichle et al.'s suggestion would predict differences in fixation positions for words with infrequent and frequent word initial letter sequences.

Another possible visual explanation for these effects is differences in visual familiarity between orthographically regular and irregular beginning words. Findlay and Walker (1999) suggested that medium and long-term learning modifies the intrinsic salience of visual stimuli such as orthographic letter sequences. Intrinsic salience then contributes to a salience map in which the distribution of salience across the visual field determines the saccade target. Importantly, different types of factors influence activity within the salience map. For example, intrinsic salience might weight the influence of the global effect (word length associated activity) such that differences in orthography simply produce small shifts in the preferred viewing positions.

Although visually based accounts of the influence of orthography on landing positions have been proposed, it is unclear whether these effects are mediated by visual or linguistic non-foveal processing. Section 1.3.3 will focus on alternative accounts that might explain such effects including attraction and extent of processing explanations.

1.3.3: Explanations: Linguistic influences on where words are first fixated

A number of accounts have been proposed suggesting that preprocessing of information beyond the level of word length can influence fixation positions. Alternative explanations for the preferred viewing position have been proposed, based on non-foveal preprocessing. Ideal observer models of eye movements in reading have suggested that lexical preprocessing might guide saccades. Furthermore, a number of suggestions have been made which might account for the effects of orthography on fixation positions. Each of these issues will be discussed in this Section.

As well as the visual and oculomotor explanations for the preferred viewing position, it has also been suggested that linguistic preprocessing might produce this phenomenon (Bouma & de Voogd, 1974; McConkie, 1979; O'Regan, 1990; Rayner, 1978; Rayner & Morris, 1992; Rayner et al., 1996). That is, the eyes might be directed to the end of the region that had been preprocessed, or expected to be preprocessed, which in many cases might be the preferred viewing position. However, Radach and McConkie (1998) suggested that, assuming that acuity limits non-foveal preprocessing, the effects of launch site on landing positions should be larger than it actually is if the effects were to be explained by the extent of preprocessing. Another possibility, suggested by Deutsch and Rayner (1999), is that the preferred viewing position places the majority of the word within the perceptual span, that is, more text is processed in the direction of the end, rather than the beginning, of the word. Farid and Grainger (1996) suggested that word beginnings tend to be more informative for distinguishing words from other lexical candidates and so fixations might be directed left of the word centre in order to increase word recognition efficiency (but see Ducrot & Pynte, 2002). Shillcock, Ellison, and Monaghan (2000) suggest that the eyes might land on the preferred viewing position because this is the optimal position in order to achieve equal processing resource requirements for the left and right hemispheres. Overall, there is currently little evidence to distinguish between these alternative explanations for the preferred viewing position. Furthermore, the phenomenon can be explained just by non-foveal preprocessing of word length and oculomotor factors and so it can not be assumed that any of these higher level processes are involved.

Nevertheless, the ideal observer Mr. Chips model (Legge et al., 1997) suggests that lexical preprocessing might be the principal factor determining fixation position. As described above, the model suggests that the fovea is simply directed to the best location to help disambiguate the identity of the next unrecognised word, regardless of word boundaries. That is, preprocessing of possible lexical candidates ensures that fixations always land on the optimal viewing position. However simulations showed that the overall optimal positions were the same for words of different length. Therefore, unlike real readers, first fixation positions are not influenced by word length. Furthermore, the method of saccade targeting in the Mr. Chips model seems unrealistic for real readers because it would require complex preprocessing of potential lexical candidate sets. Such information does not appear to be integrated across saccades, at least for preview benefits (Lima & Inhoff, 1985). Furthermore, the model might predict effects of informativeness on fixation positions, as claimed by Underwood and colleagues but disputed by other studies (see Section 1.3.1).

The remainder of this Section will be concerned with examining the nature of possible orthographic influences on fixation positions. These issues are crucial both to interpreting the results and inspiring the design of the experiments presented in this thesis. Consequently, the material presented in the rest of this Section will be discussed in detail. Some explanations of the influence of orthography on saccade programming specifically predict discrete effects whilst others are more ambiguous as to whether the predicted influence would be discrete or graded. A discrete effect is based on a categorical decision such as which word to fixate, or whether to fixate the word itself or the space between words. In contrast, a graded effect would produce landing position differences directly related to the level of orthographic regularity, hence landing positions should be nearer the word beginning for very irregular words compared to words with medium regularity, which in turn should be nearer the beginning than very regular words. Before the alternative explanations are presented, the distinction between graded or discrete effects will be explained in more detail.

Sentence reading studies that have shown small shifts in the whole of the landing position distributions (Radach et al., in press; Vonk et al., 2000) are consistent with a graded explanation of a change in fixation positions. Similar patterns have been found in studies using artificial tasks (Beauvillain & Doré, 1998; Beauvillain et al., 1996; Doré & Beauvillain, 1997). In support of a graded effect, Radach et al. show that the differences in landing positions are related to the differences in the degree of regularity. Such graded differences might be explained by differences in saccade lengths. Radach et al. reports significantly shorter saccade lengths into words with irregular beginnings and both Radach et al. and Vonk et al. present graphs showing that the mean initial landing positions on the critical words are nearer into the word for irregular than regular beginning words for each launch site. In the artificial task experiments the landing position effects are necessarily due to saccade lengths because launch site is controlled. These results suggest that there is a graded influence of orthography on fixation positions caused by differences in saccade lengths.

In contrast, other studies are more suggestive of a discrete shift in fixation positions. Hyönä (1995) showed that orthographically irregular beginning words produced little change in the preferred viewing position as a whole, but numerically more fixations on the space before the critical word compared to the orthographically regular beginning words. However, although such fixations at the word beginning tend to be associated with saccades launched from distant launch sites, there were no significant effects of orthography on either saccade length or launch site. Discrete differences in fixation positions might be caused by the discrete decision of which word to fixate. For example, if the orthographic characteristics of a word have a discrete influence on the probability of skipping or refixating the previous word then, due to discrete differences in launch site caused by the range effect, there will be discrete differences in fixation positions (see Section 1.3.1). However if there are no clear effects on prior fixation probabilities then it can be difficult to determine whether a particular pattern of results is discrete or graded. For example, in Hyönä's (1995) study it is only the descriptive data that is suggestive of a discrete effect. Note that such differences in fixation probabilities prior to fixating the critical word would also be indicative of parafoveal-on-foveal effects (see Section 1.5). Importantly, previous studies of the effects of non-foveal preprocessing on landing positions have not fully reported such possible discrete effects of launch site caused by differences in fixation probabilities. However this thesis will provide a comprehensive analysis of this variable.

Two broad types of explanation have been proposed to explain the influence of orthography on fixation positions. These are the attraction hypotheses (Beauvillain et al., 1996; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) and explanations related to general language processing (Hyönä, 1995; Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992). Both these types of accounts might predict graded or discrete effects, depending on the precise specification of each explanation. The nature and implications of the attraction explanations will first be described in some detail, followed by descriptions and evaluations of the general language processing accounts.

The attraction hypotheses are largely based on the notion that the location of non-foveal attention can modify saccade programming within words. The word "attention" is simply interpreted to mean localised processing activity. As noted earlier (Section 1.2.3, 1.2.4) this basic assumption is rather like some attention shift accounts of eye movements in reading (Morrison, 1984; Engbert & Kliegl, 2001; Engbert et al., 2002; Reilly & Radach, 2003), and like many visual perception studies

(Rizzolatti et al, 1987; Deubel & Schneider, 1996, Hoffman and Subramaniam, 1995; Kowler et al., 1995; Shepherd et al., 1986; but see Stelmach et al., 1997) which suggest that saccades follow shifts of attention. Depending on how localised these shifts of attention are, attention and saccades might be directed to word units, sub-word regions or specific letters. There could also be a gradient of attention such that attention might be allocated to a whole word but some parts of the word might be processed to a greater degree than others.

Recent studies have suggested that, at least in artificial tasks, saccades are directed to the locus of attention within a letter string. Doré and Beauvillain (1999) showed that when participants moved their eyes to an isolated letter string they were better able to identify a letter change that occurred during the saccade if the change occurred at the subsequent fixation position. This suggests that attention is localised quite specifically to the position of the subsequent fixation. If infrequent letter sequences are present then attention is less closely coupled to fixation position. However more recent experiments which manipulated the time at which the change occurred (Doré-Mazars, Pouget, & Beauvillain, 2002) suggest that although infrequent letter sequences can influence the allocation of attention, just before the saccade is executed attention is allocated to the saccade target. That is, if the change occurred long before the saccade was executed then its detection is influenced by orthographic regularity, but if the change occurred just before the saccade was executed then its detection is only influenced by the relative position of the subsequent landing position. Such results might have important implications for attention based accounts of landing position effects. For example, it could be the case that attention is drawn to irregular letter sequences and this might influence saccade programming, but ultimately other factors (such as word length) have larger influences on the localisation of attention and subsequent fixation positions. However, results from artificial tasks must be interpreted with great caution in relation to eye movements in natural reading. For example, it is possible that the letter change detection task and the presence of a single letter string encourage greater allocation of attention to the non-foveal letter string than is usually allocated during reading.

Nevertheless, the studies presented in the previous paragraph at least support the hypothesis that orthography could influence fixation positions by influencing the location of non-foveal attention. As explained in the discussion of models of eye movements in reading, McConkie (1979) originally suggested that saccades are directed to non-foveal locations of attention or processing difficulty. Underwood et al. (1990) suggested that saccades might be attracted to locations where words are not readily identified. However Pollatsek and Rayner (1990) argued that saccades are unlikely to be directed to regions of processing difficulty because the processes to compute this would take too long to be feasible within the normal range of saccade latencies. Nevertheless, more recent accounts have made more specific suggestions which might allow for more feasible programming times. Hyönä (1993b) suggested a pull assumption in which salient features (such as irregular orthography) "pop out" of non-fixated text and pull the eye towards them.

Such attraction hypotheses might predict graded or discrete effects. If the irregularity tends to influence most saccades then there might be a graded effect in the form of a shift in the entire preferred viewing position such that most saccades land on the irregular letter sequences. However if only some saccades are affected (for example, if detection depends on other factors such as general processing load) then there might be differences in the landing position distribution specifically at the site of the irregularity. Attraction hypotheses might also predict discrete effects if the attraction of saccades results in reduced probabilities of refixating the previously fixated word or increased probabilities of skipping the previous word. However graded effects in the form of small shifts in the entire preferred viewing position (Radach et al., in press; Vonk et al., 2000) are not consistent with such discrete possibilities.

Alternatively, attraction processes might influence, rather than override, the effects of other factors like word length such that they produce a graded shift in the preferred viewing position. In addition, this might help overcome Rayner and Morris' (1992) concern that the influence of within word characteristics on fixation positions would require complex processing of the saccade goal. Beauvillain and Doré (1997) suggested that abstract irregular letter sequences "pop out" of non-fixated text and influence landing positions by adjusting the word length based saccade computation. Consequently, saccades that are attracted by infrequent letters may not necessarily land on those letters. Instead, the influence of word length on fixation positions might be weighted such that infrequent letters at the word beginning would produce a small leftward shift in the preferred viewing position. Such a prediction is consistent with small graded shifts in the entire preferred viewing position (Radach et al., in press; Vonk et al., 2000). Nevertheless, a further problem with the attraction hypotheses might be whether it is indeed feasible that letter sequences could "pop-out" on the basis of abstract linguistic processing. Radach et al. (in press) noted that "pop-out" was originally associated with automatic and parallel processing of the target (Treisman & Gelade, 1980) and it is not at all clear whether abstract linguistic processing could produce such an effect.

To summarise, many studies have suggested that saccades are directed to the locus of attention. Attraction hypotheses are largely based on the idea that the orthography of a word modulates the location of attention (or processing activity) and that this influences saccade programming. However, although Doré and Beauvillain (1999) suggest that orthography does influence the location of attention, Doré-Mazars et al. (2002) show that just before the saccade is executed attention is allocated to the saccade target, rather than to irregular orthography. Furthermore, studies of the effects of orthography on landing positions have shown small shifts in the entire preferred viewing position, which suggests that saccades are not attracted directly to the location of the orthographic irregularity. In addition, it is possible that saccades might be attracted from distant launch sites by increasing the probability of skipping or reducing the probability of refixating the previous word. Such differences in fixation probabilities might produce discrete differences in landing positions as a result of the differences in launch site. However as yet there is no clear evidence for such discrete influences on landing positions. Instead, it seems that pre-processing of orthography can act to modulate the word length and launch site based saccade programme.

An alternative explanation to the attraction hypotheses and visual processing explanations is that general linguistic processing influences saccade programming. General linguistic processing accounts are based on the notion that the same processes that determine word skipping also influence fixation positions on words. Two types of general linguistic approaches will be considered. First, that the extent of non-foveal processing influences saccade programming (Hyönä, 1995; Hyönä & Pollatsek, 1998, 2000), and secondly, that the same saccade target selection processes that determine word skipping also influence fixation positions on words (Radach et al., in press; Rayner & Morris, 1992).

Hyönä (1995) initially proposed that irregular word beginnings produce processing difficulty which causes the target of the saccade to be changed to the space before the word. Such an account is consistent with the view that coarse visual features guide saccades. Hyönä's suggestion would explain the discrete effect of irregular words producing more fixations on the space before the word in Hyönä's (1995) experiment. However, such an explanation is not consistent with the graded shifts in the entire preferred viewing position shown in later studies (Radach et al., in press; Vonk et al., 2000). Hyönä and Pollatsek (1998, 2000) later proposed that processing difficulty reduces the perceptual span or the extent of preprocessing (Henderson & Ferreira, 1990), and this shortens saccades. Note that this account is an extension of the notion that the eyes are directed to the end of the region that has been preprocessed (Bouma & de Voogd, 1974; McConkie, 1979; O'Regan, 1990; Rayner, 1978; Rayner & Morris, 1992; Rayner et al., 1996) as discussed in relation to the preferred viewing position above. Hyönä and Pollatsek (2000) explain that the weak version of the processing difficulty hypothesis suggests that processing load within words affects the probability of skipping and refixating words and the strong version suggests that processing load affects saccade length to and within words. Consequently, in terms of the influence of letter sequence frequencies on fixation positions, the processing difficulty account predicts that the effects are entirely driven by differences in saccade lengths. Whether the effects are discrete or graded depends on how closely the extent of the perceptual span is tied to the location of the orthographic irregularities. Hyönä and Pollatsek's account can also explain influences of other types of processing difficulty on fixation positions, such as that caused by morphology. However, the hypothesis does not specify exactly what kinds of non-foveal information can induce processing difficulty and so influence saccade lengths.

Hyönä and Pollatsek's (2000) processing difficulty hypothesis might be tested on the basis of three fundamental assumptions. First, the account only predicts effects of orthography on saccade length, not launch site. Secondly, if saccades are to be directed to the extent of processing that has been undertaken by the end of the previous fixation, then adjustments to the saccade programme must be made late during the previous fixation. Thirdly, the account predicts that the effects of orthography are limited by general processing load. The third assumption might also apply to other general linguistic processing accounts, and will therefore be evaluated along with these after they have been described. The first test is whether landing position effects can be explained entirely by differences in saccade length. Hyönä and Pollatsek's (1998, 2000) processing difficulty hypothesis does not predict any effect of non-foveal difficulty on launch site. Consequently, it is difficult for this account to explain the results of studies which do not find effects of saccade length corresponding to the landing position effects (e.g. Hyönä, 1995). However if there are effects of saccade length and no effects of launch site (e.g. Radach et al., in press) then it is more difficult to distinguish between the alternative explanations. The second test is at what time non-foveal difficulty can influence saccade programming.

It is assumed that the extent of processing varies during the course of a fixation. Therefore, in order to produce an accurate saccade to the extent of processing, then a judgement of the extent of processing must be made at the end of the previous fixation. Consequently, the saccade programme would have to adjust late during the previous fixation. In contrast, the attraction hypotheses could potentially exert an influence at any time during a fixation. Therefore, one approach to testing these accounts might be to examine at what time during the previous fixation orthography influences saccade programming. Doré and Beauvillain (1998) showed that the orthographic regularity of a letter string did not influence where it was fixated when the saccades were delayed by 150ms, but orthography did affect fixation positions when there was no delay. On the basis of this result, Doré and Beauvillain suggest that the influence of orthography on fixation positions is driven by preattentive automatic encoding of orthography. However, it is not at all clear whether the same might apply to continuous reading situations in which there are greater attentional demands, especially at the point of fixation. Nevertheless, Morris et al. (1990) showed that the presentation of non-foveal letter information influenced subsequent saccade lengths if it was available by 150ms into the fixation, which supports the possibility that orthography might influence saccade programming early in the fixation. However, it is difficult to evaluate the alternative accounts of landing position effects on the basis of these studies. For example, it is not entirely clear at what time within a fixation the extent of processing accounts would select the extent of processing as the saccade target.

As noted above, Hyönä and Pollatsek (2000) suggest that a weak version of their hypothesis might explain which words are fixated and a strong version might explain where words are fixated. Similarly, other general linguistic processing based accounts also explain the influence of orthography on fixation positions by the same processes that determine word skipping. Rayner and Morris (1992) suggested that parts of words, such as orthographically regular letter sequences, might be skipped which could produce differences in fixation positions. Rayner and Morris claimed that this possibility is unlikely because if the effects were due to skipping then prior fixation durations should be inflated, however, studies showing effects of non-foveal processing on landing positions have not produced such inflated prior fixation durations. Nevertheless, note that although some studies have reported inflated fixation durations prior to word skipping (Hogaboam, 1983; Pollatsek, Rayner, & Balota, 1986; Reichle et al., 1998) others have not shown such effects (Drieghe, Brysbaert, Desmet, & De Baecke, in press; Radach & Heller, 2000). Therefore, it is possible that Rayner and Morris' suggestion may indeed explain landing position results.

Another explanation that is again related to general linguistic processing is a suggestion made by Radach et al. (in press). As explained in Section 1.2.3 Reilly and Radach's (in press) Glenmore model explains word skipping by suggesting that linguistic information is used to influence the activity of word letter strings within a salience map. Radach et al. suggest that if the linguistic feedback was specific to each letter, rather than just each word, then orthographic characteristics of a word would influence activation within a salience map and therefore saccade targeting. According to Hyönä and Pollatsek's (2000), Rayner and Morris' (1992) and Radach et al.'s (in press) suggestions, the same types of processing that influence which words are fixated might also influence saccade programming to words. However such accounts might predict effects such as shorter saccades into high frequency than low frequency words, for which there is no evidence (Rayner et al., 1996).

There is currently limited evidence to distinguish between the attraction and general linguistic processing explanations. As explained above, the processing difficulty hypothesis (Hyönä & Pollatsek, 1998, 2000) might be tested by examining whether landing position effects are entirely explained by saccade lengths and at what time orthography influences saccade programming. However, neither of these provides strong tests of the approach. However a third possibility is to assess the assumption that general processing load limits non-foveal preprocessing. The processing difficulty hypothesis, and perhaps other linguistic processing accounts (Radach et al., in press; Rayner & Morris, 1992), predict that general processing difficulty should reduce processing of non-foveal words, and consequently reduce the influence of non-foveal difficulty on saccade programming.

The general linguistic processing explanations can therefore be tested by investigating whether the effect of non-foveal orthography on fixation positions is reduced when there is high foveal processing load. Liversedge and Underwood (1998) attempted to investigate this issue but neither of their processing difficulty manipulations was effective. Foveal processing difficulty (category typicality and gender role typicality) did not influence foveal reading time measures and non-foveal processing difficulty (orthography) did not influence landing positions. If contextual predictability modulates non-foveal processing then the processing difficulty hypothesis might also predict larger effects of orthography when the critical word is unpredictable because the orthographic irregularities might be much easier to process when the word is predictable. However no such effects have been shown (Everatt et al., 1998; Vonk et al., 2000; Zola, 1984). Nevertheless, the issue of whether landing position effects are modulated by general processing difficulty is crucial to evaluating the attraction and general linguistic processing accounts.

To summarise, the general linguistic processing accounts suggest that fixation positions are influenced by the extent of non-foveal processing (Hyönä & Pollatsek, 1998, 2000) or similar processes to those that determine word skipping (Radach et al., in press; Rayner & Morris, 1992). The extent of processing accounts imply that orthography must influence saccade programming late during the previous fixation in order to have an accurate judgement of the extent of non-foveal processing. However, the results of Doré and Beauvillain (1998) and Morris et al. (1990) suggest that orthography might influence saccade programming earlier, rather than later, in the fixation. Nevertheless, it is difficult to use this evidence to evaluate the extent of processing account because there is no clear prediction about exactly when the extent of processing judgement would be made during a fixation. That is to say, it has not been specified whether the extent of processing judgement is made in the last 50, 100 or 150 milliseconds of a fixation. It is also unclear what kinds of non-foveal processing can influence the general linguistic processing accounts. The results of a number of studies (see Section 1.3.1) suggest that lexical processing cannot influence fixation positions, but the general linguistic processing accounts might predict such effects. However, perhaps the strongest test of the general linguistic processing accounts is whether the effects are limited by general linguistic processing resources. Consequently the effect of general processing difficulty on the modulation of landing positions by orthography will be investigated in Chapter 5.

Overall, it has been suggested that the preferred viewing position might be explained by preprocessing of linguistic information. However, visual explanations can explain this effect equally well. In addition, although an ideal observer model of reading has suggested that preprocessing of lexical information can influence saccade programming, there is little evidence to support this. The strongest evidence for linguistic preprocessing influences on saccade programming is that orthographic regularity influences where words are fixated. Section 1.3.2 suggested two visually based accounts of these effects based on low spatial frequency processing of letter shapes or visual familiarity. Alternatively, irregular orthography may "pop-out" or attract attention which might then attract saccades towards the irregular letter sequences or influence the word length based saccade computations. Alternatively, fixation positions might be influenced by general linguistic processing such as the extent of the perceptual span or word skipping processes. However, as yet there is little strong evidence to support any of the explanations of orthographic landing position effects over the others.

1.3.4: Summary: What determines where words are first fixated

Section 1.3.1 showed that visual and oculomotor factors, such as word length and launch site, are most important in determining where words are first fixated. However, there is also evidence to suggest that more complex characteristics of words can also influence the position of initial fixations on them. Three studies suggest that the orthography of words can influence where they are fixated in the reading of text. However, there is still no strong evidence that orthography influences where words are first fixated in English, or that letter sequence frequencies (rather than individual letters) influence fixation positions in any language. Therefore most models of eye movements in reading suggest that initial fixations depend largely on word length, systematic range error due to launch site and random oculomotor error, they do not account for any influence of orthography.

The present thesis includes a series of experiments that aim to address whether orthography does influence initial fixation positions on words and how these effects might be explained. Namely, experiments will investigate if word initial letter sequence frequency can influence fixation positions in the reading of English sentences. Additional experiments will examine whether such effects might be explained by visual processing of low spatial frequency features, as suggested by Reichle et al. (in press). The experiments will also provide a strong test of whether the attraction or general linguistic processing accounts can best explain the results. The investigation of these issues raises two further important questions. First, can the characteristics of a word influence where words are refixated? Secondly, if the characteristics of a word influence initial fixation positions on that word, are previous fixations (during which those saccades are programmed) also influenced by the same factors? These issues will be considered in the final two main Sections (1.4 and 1.5 respectively).

1.4: What Determines Where Words are Refixated

Visual and linguistic factors have been shown to influence which words are fixated (Section 1.2.1) and where words are first fixated (Section 1.3.1). Similarly, this Section will show that both these factors also influence programming of refixation saccades within words. As in the previous two sections, both visual and linguistic explanations for what determines the programming of refixation saccades will be considered and evaluated in relation to the evidence. Note that, compared to the issue of where words are first fixated, very few studies have investigated what determines where words are refixated. Therefore the accounts of previous evidence and possible explanations will necessarily be brief.

Word length and launch site have been shown to be the primary factors influencing the position and length of refixation saccades. O'Regan (1990) argued that the locations of refixations are determined by the position of the first fixation on a word in relation to the word length. That is, refixations are directed to the opposite end of the word to the initial fixation position. Other studies suggest that refixations might be preprogrammed on the basis of word length (Vergilino & Beauvillain, 2000, 2001).

As with the literature for initial fixation positions on words, evidence also suggests that more complex information than word length can influence refixation saccades. Studies suggest that the distribution of information within a word influences the location of refixations. Pynte, Kennedy and Murray (1991) used a word by word reading presentation technique in French in which the words could be presented in order that fixations were positioned on particular regions of words. It was found that if the eye was directed to the word beginning then refixation saccades were shorter if the word beginning, rather than the end, is informative. Pynte (1996) used a similar task with unrelated words and showed that refixations are directed to orthographically informative regions of the text (see also Pynte, 2000). Hyönä et al. (1989) also showed that the distribution of information within isolated words influenced refixation saccade lengths. In addition, Hyönä (1995) demonstrated that refixation saccades tend to be shorter for words with orthographically irregular beginnings. Underwood et al. (1988) and Underwood et al. (1987) showed that the distribution of information within words influenced the number of fixations that were made at the beginning and ends of words. There is also some evidence to suggest that morphological information can influence refixation saccades. Hyönä and Pollatsek (1998) demonstrated that refixation saccades were shorter if the initial morpheme of Finnish compound words was short rather than long. Furthermore, they also showed that refixation saccades were shorter if the initial morpheme was infrequent compared to if it was frequent (see also Bertram & Hyönä, 2003). Therefore evidence from both artificial tasks and sentence reading experiments show that the linguistic characteristics of words influence the position or length of refixation saccades.

Most models of eye movements in reading do not provide any clear account of what determines where refixation saccades land within words. O'Regan (1990) suggested that if the initial fixation is not optimal a rescue tactic is used such that a refixation is made to the other side of the word from the initial fixation position. McConkie (1979) suggested that refixation saccades might be targeted by saccades following shifts of attention to particular regions within the attended word, although it is not specified what factors might influence the allocation of attention. The attraction and general linguistic processing accounts discussed in Section 1.3.3 might also be used to explain how linguistic factors might influence refixation saccade programming.

Overall, it is clear that both visual and linguistic factors influence refixation saccades but few explanations have been proposed to explain these effects. The present thesis will undertake further tests of whether the characteristics of words can influence the programming of refixation saccades. In addition, the experiments will investigate if the characteristics of words influence prior fixations (parafoveal-on-foveal effects).

1.5: Parafoveal-on-foveal Effects

A small number of studies (Hyönä, 1995; Radach et al., in press; Vonk et al., 2000) have suggested that the orthographic characteristics of words can influence where words are first fixated when we read. In order for orthography to influence saccade programming, the orthographic characteristics of the words must have been preprocessed on the previous fixation. It is possible that non-foveal characteristics can influence saccade programming without influencing the durations or fixation probabilities on previous fixations. For example, Reichle et al. (in press) suggest that early visual processes influence saccade programming independent of word recognition based processes that determine when the eyes move or which words are fixated. Also, it is possible that non-foveal features might influence saccade programming after the decision to move the eyes has been made (Becker & Jürgens, 1979; for saccade sizes similar to reading see Findlay & Harris, 1984). However other accounts suggest that non-foveal characteristics could influence fixation durations or probabilities before those features have been fixated. For example, if infrequent letter sequences attract the eyes towards them, this might also trigger those saccades to occur earlier. Hence the probability of skipping the previous word might be increased, the probability of refixating the previous word might be reduced and prior fixation durations might be smaller. Note that the attraction explanations described in relation to landing position effects (Section 1.3.3) are similar to attraction explanations of parafoveal-on-foveal effects (Kennedy, 1998), both these accounts might predict parafoveal-on-foveal effects on fixation probabilities.

Parafoveal-on-foveal effects are often cited as evidence that multiple words might be processed in parallel (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Reilly & Radach, 2003; Schiepers, 1980), in contrast to the serial attention shift accounts of eye movements in reading (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press; Suppes, 1990, 1994). Parallel processing implies that the characteristics of a word that have not yet been fixated can be processed at the same time as a fixated word and can therefore influence eye movement behaviour on that word. The investigation of parafoveal-on-foveal effects is therefore crucial in evaluating the models of eye movements in reading. The issue is especially relevant here because parallel processing accounts might predict that the same non-foveal characteristics that are preprocessed and influence saccade programming might also influence fixation patterns on previous words. However, Hyönä (1995) found no effects of orthography on prior fixations and Radach et al. and Vonk et al. do not report such analyses. The evidence for such effects in other studies has so far been quite mixed.

A number of studies have reported that fixation durations or fixation probabilities are influenced by the orthographic (Inhoff, Starr, et al., 2000; Rayner, 1975b; Underwood, Binns, & Walker, 2000; Vitu, Brysbaert, & Lancelin, in press; Starr & Inhoff, in press) and lexical (Inhoff, Radach et al., 2000; Kennedy, 1998, 2000b; Kennedy, Murray, & Boissiere, in press; Kennedy, Pynte, & Ducrot, 2002; Pynte, Kennedy, & Ducrot, in press; Lavigne et al., 2000; Murray, 1998; Murray & Rowan, 1998) characteristics of the following word. Artificial tasks are often used to investigate such parafoveal-on-foveal effects. For example, Kennedy (1998, 2000b) used the "looks-means" task in which subjects look at a series of isolated words and make a matching or semantic judgement, and the "clothing search" task in which subjects look at a series of isolated words and judge if any of them is an item of clothing. However the direction of the effects in these studies is often inconsistent (Hyönä & Bertram, in press a) and there are concerns about the generalizability of some of the findings (Rayner, White, Kambe, Miller, & Liversedge, 2003). For example, in a sentence reading experiment Underwood et al. (2000) reported that fixations on the foveal word were longer when word n+1 had an informative initial trigram. In contrast, in artificial task experiments by Kennedy (1998, 2000b) fixations on the foveal word were shorter when word n+1 had an informative initial trigram. Furthermore, many studies have not shown parafoveal-on-foveal effects. For example, studies have shown no effect of word frequency on prior fixation durations (Carpenter & Just, 1983; Henderson & Ferreira, 1993; Kennison & Clifton, 1995; Rayner, Fischer et al., 1998; Schroyens et al., 1999).

Despite the contradictory evidence, the results of studies showing parafoveal-on-foveal effects have important implications for models of eye movements in reading. Effects of the orthographic characteristics of word n+1 on fixation durations on the previous word might be explained by serial processing of words. Some studies have shown that the orthographic characteristics of word n+1 can lengthen fixation durations at the very end of word n (Rayner, 1975b). Such effects might be explained by oculomotor error, saccades might have been targeted to word n+1 and so reflect processing of word n+1, but they actually undershot and so landed at the very end of word n. However other results, such as differences in refixation and skipping probabilities on word n-1 (Kennedy, 1998; Kennedy et al., 2002; Pynte et al., in press) are more difficult for serial processing models to account for. Note that such differences in fixation probabilities might be similar to those predicted by the attraction hypotheses as explained in Section 1.3.3. Importantly, parallel processing accounts predict that orthographically irregular words should influence fixation durations or fixation probabilities on the previous word. The experiments in this thesis test this prediction.

1.6: Summary and Thesis Outline

Many studies have shown that the orthographic characteristics of non-foveal words can be preprocessed and facilitate processing when those words are subsequently fixated. Furthermore, lexical characteristics of foveal and non-foveal words can also be preprocessed such that they influence the probability of refixating and skipping words. However, there are only a few studies which suggest that orthographic preprocessing can impact on saccade programming such that it influences where words are first fixated. Studies that have shown such effects have not properly controlled for individual letter frequency and have been undertaken in languages other than English. A few other studies have failed to find such effects. This thesis includes a series of experiments that provide strong tests of the hypothesis that orthographic preprocessing can influence where words are first fixated and refixated in the reading of English. The experiments also test whether the orthographic characteristics of a non-foveal word can influence eye fixation behaviour on the previous word. This thesis also tests the predictions of models of eye movements in reading. Most current models of eye movements in reading do not attempt to explain any influence of orthography on where words are first fixated or refixated. In addition, parallel processing accounts predict that the orthographic characteristics of a word should influence fixation probabilities or durations on the previous word. The experiments in this thesis address these fundamental issues.

Chapters Two and Three report experiments that address whether orthographic or lexical processes influence where words are first fixated when they are misspelled compared to when they are spelled correctly. Chapter Four tests whether orthography influences where correctly spelled words are first fixated and examines whether these effects generalise to visually less distinctive (upper case) text. Chapter Five tests whether the effects of orthography on fixation positions are better explained by extent of processing or alternative explanations. The final chapter (Chapter Six) evaluates the implications of the results of all of the experiments for current models of eye movements in reading and for specific accounts of fixation positions on words.

Chapter 2

Fixation Positions on Misspelled Words

Section 1.3.1 reviewed previous studies that have tested whether non-foveal processing beyond the level of word length can influence where words are first fixated. Some studies have suggested that lexical preprocessing related to the distribution of information within words can influence where words are first fixated (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987) but other studies have not shown such effects (Beauvillain et al., 1996; Hyönä, 1995; Rayner & Morris, 1992; Underwood et al., 1989). Similarly, some sentence reading studies have suggested that orthographic preprocessing can influence where words are first fixated (Hyönä, 1995; Radach et al., in press; Vonk et al., 2000) but again other studies have not shown such effects (Liversedge & Underwood, 1998; Radach & Kempe, 1993; Radach & McConkie, 1998). Section 1.4 also explained that there is a debate as to whether linguistic or visual factors guide the programming of refixations. The purpose of Experiment 1 was therefore to provide a strong test of the hypothesis that the characteristics of words beyond the level of word length can influence where words are first fixated and refixated.

As explained in Section 1.5, the experiments also provide an opportunity to test if the characteristics of a word influence fixation durations and probabilities prior to fixating it. Serial attention shift accounts of eye movements in reading (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press) predict that processing of word n+1 can not usually influence prior fixations. In contrast, parallel attention allocation explanations (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980) suggest that because multiple words can be processed simultaneously, the characteristics of word n+1 might influence prior fixation patterns. If such parafoveal-on-foveal effects are robust then there should be consistent effects or orthography on eye movement behaviour on the previous word. For each of the experiments presented in this thesis, parafoveal-on-foveal effects on the duration of prior fixations and prior fixation probabilities are examined. Each Results section begins with a sub-section on parafoveal-on-foveal effects which examines whether the characteristics of the critical string influence the duration of the fixation prior to first fixating the critical string and first fixations or gaze durations on the word prior to the critical string. In addition, any parafoveal-on-foveal effects of fixation probabilities would also have important implications for launch sites prior to fixating the critical string. Therefore the effects of the critical string on the probability of skipping or refixating the word prior to the critical string is presented within the section on incoming saccade extent and launch site.

Section 2.1 explains a number of experimental controls that were applied in all of the experiments in this thesis. Section 2.2 presents the details of Experiment 1, beginning with an outline of the experimental conditions and the predictions on the basis of previous studies and models.

2.1: Experimental Controls

All of the experiments in this thesis used a natural reading methodology in which participants read single line sentences. Critical words (referred to as critical strings when misspelled) were embedded within sentences such that words from each condition were embedded within the same sentence frame. Such counterbalancing ensures that any effects of the sentence frames are the same for each condition. Nevertheless, in order to reduce the variability in eye movement behaviour caused by differences in the sentence frames, a number of basic controls were employed for each of the experiments. As described in Section 1.3.1, previous studies have shown that fixation patterns on the previous word can influence fixation positions on the subsequent word (Radach & Kempe, 1993; Radach & McConkie, 1998). Consequently the word before the critical string was always five or six letters long. Preceding the critical string by five or six letter words should increase the number of fixations on the critical string that follow a single fixation on the previous word. Kennedy et al. (2002) argued that previous studies have shown inconsistent patterns of parafoveal-on-foveal effects because the foveal word (in this case the five or six letter word) was not controlled for length. Therefore by controlling the length of word n-1 the patterns of fixations prior to the critical string should be as consistent as possible and the possibility of detecting parafoveal-on-foveal effects is maximised.

The critical strings were always presented approximately in the middle of the sentence in order that a full preview of the string was available before it was fixated and to reduce the possibility of the effects being influenced by clause wrap up processes. In addition, participants always read at least six practice sentences at the beginning of the experiment in order for them to become accustomed to the experimental situation before the experimental sentences were presented. In all of the experiments participants responded "yes" or "no" to comprehension questions on approximately one third of the trials. The comprehension questions ensured that participants concentrated on understanding the sentences and gave a measure of their ability to do this.

2.2: Experiment 1

As stated above, Experiment 1 was designed to provide a strong test of the hypothesis that preprocessing of non-foveal words, beyond the level of word length, can influence where words are first fixated. The aim was to compare different types of orthographic regularity in order to test what kinds of non-foveal characteristics might influence initial landing positions on words. In order to provide the strongest possible test of this hypothesis, letter strings were presented with initial letter sequences that were so irregular that they did not exist in the language. In order to undertake such a manipulation it was necessary to use misspelled words.

Zola (1984) undertook a reading experiment comparing saccades into correctly spelled words with saccades into words misspelled with different degrees of "spelling degradation". Four conditions involved changing the fourth letter of the word and a fifth condition involved changing the first, fourth and last letters of the word. Zola showed that saccade lengths into the critical words were significantly shorter in the fifth (most "degraded") condition compared to the correctly spelled condition. On the basis of this result, Zola argued that orthographic characteristics of words can influence saccade lengths into words. However, it is not clear if spelling also influenced fixation positions on the critical words. Underwood et al. (1988) found no significant differences between correctly spelled words and words with the third letter misspelled for saccade lengths into or landing positions on the critical strings. However it is possible that the misspellings were too far into the word to have a strong effect on saccade programming. Neither Zola (1984) nor Underwood et al. controlled the frequencies of the word initial letter sequences in the correct and misspelled conditions. Experiment 1 uses a similar design to that of Zola, but the misspellings were always on the first or second letter of the word and the word initial letter sequence frequencies were experimentally manipulated.

In Experiment 1, a correctly spelled condition with frequent word initial trigrams (e.g. *agricultural*) was compared to four misspelled conditions. Three of the misspelled conditions had different degrees of orthographic regularity in order to investigate the characteristics of an orthographically unfamiliar string that influence saccade computation. The most irregular misspelling condition formed an illegal unpronounceable word initial trigram (e.g. *ngricultural*). The word "illegal" indicates that no word in the English language begins with such an initial trigram. A second condition formed an illegal but pronounceable word initial trigram (e.g. *akricultural*). The third misspelled condition had word initial trigrams that occurred in the lexicon but which were low in frequency (e.g. *aoricultural*). The results of sentence reading studies showing that preprocessing of orthography influences where words are first fixated (Hyönä, 1995; Radach et al., in press; Vonk et al., 2000) suggest that the illegal unpronounceable, illegal pronounceable and low frequency misspelling conditions should produce initial fixation positions nearer the word beginning than the correctly spelled condition. In contrast, models of eye movements in reading currently predict no such effects (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990).

The three orthographically irregular misspelling conditions necessarily confounded the orthographic regularity of the initial trigram with the presence of a misspelling. As a result, a fourth misspelling condition was included in which the word initial trigrams had high frequencies equivalent to the correctly spelled condition (e.g. *acricultural*). There were no differences in the initial bigram and trigram frequencies between the correctly spelled and high frequency misspelled conditions. Therefore, if only orthographic preprocessing of the word initial letters can influence first fixation positions then there should be no difference in initial fixation positions between the correctly spelled and the high frequency misspelling conditions. However, some studies have suggested that lexical preprocessing may influence where words are first fixated (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987). These studies might predict that fixation positions should be nearer the beginning of high frequency misspelled words than correctly spelled words because the misspellings create lexically more informative letter sequences near the beginning of the high frequency misspelled words compared to the correctly spelled words. As with the manipulations of orthography, current models of eye movements in reading predict no differences between these conditions.

2.2.1: Method

Participants. Forty-five members of the University of Durham community participated in the experiment. All of the participants were native English speakers with normal or corrected to normal vision. The participants were paid to participate and all were naïve in relation to the purpose of the experiment.

Apparatus. The sentences were presented on a ViewSonic 17GS monitor with the default graphics characters in Borland C++. The monitor was interfaced with a computer through a VGA board. The sentences were displayed at a viewing distance of 70cm and three and a half characters subtended one degree of the visual angle. The room was dimly illuminated. The letters were presented in light cyan (by mixing the green and blue input signals on the monitor) on a black background.

Eye movements were monitored using a Fourward Technologies Dual Purkinje (Generation 5.5) eye tracker which was interfaced with the computer. The resolution of the eye tracker is less than 10 min of arc and the sampling rate was every millisecond. Eye movements were recorded from the right eye though viewing was binocular.

Materials and Design. Word frequencies and n-gram frequencies were based on the CELEX English word form corpus (Baayen, Piepenbrock, & Gulikers, 1995). There were 35 critical strings with a mean word length of 9.7 characters (range 8 to 13) and a mean word frequency of 41 counts per million (*SD* = 53). Stimuli were chosen on the basis of token frequency, but type frequencies followed similar patterns. Type frequency is the total number of words that contain a particular letter sequence. Token frequency is the sum of the frequencies of the words that contain a particular letter sequence. All of the type and token frequencies were position specific unless otherwise specified. N-gram frequencies were based on counts per 17.9 million because this is a more sensitive measure.

There were five spelling conditions that were manipulated within participants and items. In the baseline condition the critical string was spelled correctly with a high frequency initial trigram (e.g. *agricultural*). In the high frequency (e.g. *acricultural*), low frequency (e.g. *aoricultural*) and the illegal pronounceable (e.g. *akricultural*) misspelled conditions the second letter of the word was misspelled. In the illegal unpronounceable (e.g. *ngricultural*) misspelled condition the first letter was misspelled if the original first letter was a vowel (21 items) and the second letter was misspelled if the original first letter was a consonant (14 items). There were 35 items in all of the conditions except for the illegal pronounceable misspelled condition in which there were 30 items. Five critical strings did not have illegal pronounceable misspellings because there were no suitable letters that could meet the necessary constraints. Therefore the items analyses were based on 30 items and the participants analyses were based on 30 items in the illegal pronounceable condition and 35 items in each of the other four spelling conditions.

The token frequencies for the initial trigams were high for both the correctly spelled (M = 14514, SD = 17465) and the high frequency misspelled (M = 11345, SD = 12848) conditions. The stimuli were chosen primarily on the basis of token frequency but type frequencies for the initial trigrams also tended to be high for both the correctly spelled (M = 75, SD = 88) and the high frequency misspelled (M = 68, SD = 115) conditions. The position in the word at which the high frequency misspelled words became illegal was uncontrolled. The position ranged from four to seven characters and the mean position was 4.6 characters (SD = 0.88). In the low frequency misspelled condition the initial trigram mean type (M = 3, SD = 3) and token frequencies (M = 68, SD = 63) were low. For the illegal pronounceable and the illegal unpronounceable misspelled conditions the initial trigram never occurred in the lower case corpus. For the correctly spelled and the high frequency misspelled conditions there were no significant differences between the initial trigram type or token frequencies (t's < 1). There were significant differences in the initial trigram type and token frequencies between the correctly spelled and the high frequency misspelled conditions compared to the low frequency and illegal initial trigram conditions (t's > 3.3, ps < .01). The type and token initial bigram frequencies were high for the correctly spelled and high frequency misspelled conditions but low for the low frequency and illegal misspelled conditions. There were no significant differences in the initial or second (second and third letter) bigram type and token frequencies between the correctly spelled and the high frequency misspelled conditions (t's < 1.5). There were significant differences in initial bigram type and token frequencies between the correctly spelled and the high frequency misspelled conditions compared to the low frequency misspelled conditions and the illegal misspelled conditions (t's > 3.8, $ps < .01$).

The critical strings in each condition were placed in identical sentence frames. Each of the sentences was no longer than one line of text (78 characters) and the critical strings appeared approximately in the middle of the sentence. The words before (word n-1) and after (word n+1) the critical string were either five or six letters long and had medium to high frequencies.

Five lists of 171 sentences were constructed and nine participants were randomly allocated to each list. Each list included 34 experimental sentences of which six items were from the illegal pronounceable condition and seven items were from each of the other four conditions. The conditions were rotated following a Latin square design. There were 30 misspelled filler sentences with the misspellings in a variety of word lengths and positions. There were also 107 filler sentences that were spelled correctly. Therefore of the 171 sentences, 57 contained a misspelling. Fifty-eight of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences. The sentences were presented in a fixed random order with eight filler sentences at the beginning. See Appendix A for examples of experimental sentences and critical strings.

Procedure. Participants were instructed to ignore the misspellings and to concentrate on understanding the sentence to the best of their ability. A bite bar and head restraint were used to minimize head movements. The initial calibration procedure lasted approximately five minutes. Every few trials participants were asked to look at boxes on the far left, centre and far right of the screen in the place of the sentence and a moving box represented the computed eye position. The eye-tracker was re-calibrated if the recordings were inaccurate. If the recordings were accurate the participant looked at the far left box before the experimenter presented the next trial. After reading each sentence the participants pressed a button to continue and used a button box to respond "yes" or "no" to comprehension questions. The entire experiment lasted approximately 45 minutes and participants were given two breaks.

Analyses. Fixations shorter than 80ms that were within one character of the next or previous fixation were incorporated into that fixation. Any remaining fixations shorter than 80ms and longer than 1200ms were discarded. Analyses of word n-1, the critical string and word n+1 included the space before the respective word in each case.

Five percent of trials were excluded due to either no first pass fixations on the sentence prior to word n-1 or tracker loss or blinks on first pass reading of word n-1 or the critical string. Five participants were replaced due to more than 15 percent of trials being excluded in this manner and one participant was replaced due to an error rate greater than 15 percent on the comprehension questions.

2.2.2: Results

Repeated measures analyses of variance (ANOVAs) were undertaken across the five spelling conditions, with participants (F_1) and items (F_2) as random variables. If there were significant main effects across both participants and items then simple effects were computed comparing the correctly spelled condition with each of the misspelled conditions. Paired samples t-tests were undertaken across both participants (t_1) and items (t_2) for comparisons between pairs of variables. The duration of the first fixation, gaze duration (the sum of fixations on a word before leaving it) and total time (the sum of all fixations within a word) were calculated for word n-1, the critical string and word n+1. Landing positions, incoming saccade extent and launch site were analysed for the initial first pass fixation on the critical string. The frequency, direction and length of refixation saccades on the critical string were also analysed. The mean error rate on the comprehension questions was five percent, indicating that participants properly read and understood the sentences.

Table 2.1 *Experiment 1. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Standard Deviations Shown in Parentheses.*

Experiment 1	Word n-1		Fixation n-1		
	FF	GD	All	n-1	≤3
Correct	267 (85)	291 (113)	257 (85)	264 (87)	267 (90)
High frequency misspelling	267 (83)	291 (112)	256 (82)	267 (83)	261 (83)
Low frequency misspelling	260 (71)	281 (88)	253 (74)	255 (70)	245 (69)
Illegal pronounceable misspelling	272 (91)	298 (121)	257 (85)	268 (87)	257 (84)
Illegal unpronounceable misspelling	269 (96)	298 (121)	262 (92)	270 (97)	255 (76)

Parafoveal-on-foveal effects. Table 2.1 shows the mean reading time measures on word n-1 and mean fixation durations prior to fixating the critical string. For word n-1 there were no significant effects of spelling on first fixation or gaze duration (F's < 1.2). There was no significant effect of spelling on the duration of the fixation prior to the first fixation on the critical string for all of the data (F's < 1), for only those trials when the prior fixation was on word n-1, $F_1(4, 176) = 1.42, p = .231, MSE = 1470$; $F_2 < 1$, and for only those trials when the prior fixation was three or less characters away[1], $F_1(4, 144) = 1.27, p = .284, MSE = 3556$; $F_2 < 1$. These data provide no evidence of parafoveal-on-foveal effects on prior fixation durations.

[1] For Experiment 1, the F_1 analysis of saccades launched from three or less characters away was based on data from 37 participants due to eight participants failing to fixate or having excluded data for these characters in at least one of the conditions.

Table 2.2 *Experiment 1. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String and Word n+1. Fixation Duration After Leaving the Critical String (Fixation n+1). Standard Deviations Shown in Parentheses.*

Experiment 1	Critical string			Fixation	Word n+1		
	FF	GD	TT	n+1	FF	GD	TT
Correct	276 (97)	339 (143)	385 (193)	263 (73)	271 (75)	279 (86)	312 (131)
High frequency misspelling	297 (117)	428 (273)	618 (391)	264 (95)	278 (100)	302 (122)	380 (206)
Low frequency misspelling	301 (122)	478 (295)	640 (397)	269 (102)	285 (106)	314 (124)	366 (183)
Illegal pronounceable misspelling	301 (121)	478 (304)	642 (406)	266 (109)	282 (122)	310 (132)	367 (181)
Illegal unpronounceable misspelling	318 (145)	507 (327)	677 (420)	276 (104)	280 (105)	302 (127)	363 (179)

Reading time measures. Table 2.2 shows the mean reading time measures on the critical string. There was a significant effect of spelling on the reading time measures on the critical string for first fixation, $F_1(4, 176) = 5.28, p < .01, MSE = 1803$; $F_2(4, 116) = 4.43, p < .01, MSE = 1727$, gaze duration[2], $F_1(3.5, 152.2) = 18.06, p < .01, MSE = 12744$; $F_2(2.7, 79.6) = 13.83, p < .01, MSE = 17027$, and total time, $F_1(3.2, 141.8) = 33.74\ p < .01, MSE = 23511$; $F_2(2.9, 83.8) = 18.49, p < .01, MSE = 36519$. For all of these measures the correctly spelled words were fixated for a significantly shorter time than the misspelled conditions, F's > 4.6, ps < .05. There were also significant differences between the high frequency and the illegal unpronounceable misspelled conditions on the critical string for first fixation duration, $t_1(44) = 2.02, p = .05$; $t_2(34) = 2.23, p = .03$, and gaze duration, $t_1(44) = 3.23, p < .01$; $t_2(34) = 2.55, p = .02$, which suggests that the words with more irregular misspellings were more difficult to recognise than the words with less irregular spellings.

---

[2] If a Mauchly test of sphericity was significant, the Greenhouse-Geisser Epsilon adjustment was used. Unless otherwise indicated, if the degrees of freedom do not correspond to the number of conditions and participants or items then the results were corrected for sphericity.

Table 2.2 also shows the mean reading time measures on the word following the critical string. There was no effect of spelling on the duration of the fixation after leaving the critical string (F's < 1) or on the first fixation on word n+1 (F's < 1). Although there was a significant effect of spelling on gaze duration on word n+1 across participants this was not significant across items[3], $F_1(4, 168) = 3.44, p = .01$, $MSE = 2309$; $F_2(4, 116) = 1.93, p = .11, MSE = 2571$. However spelling did significantly influence total reading times on word n+1, $F_1(4, 176) = 5.51, p < .01$, $MSE = 4807$; $F_2(4, 116) = 4.16, p < .01, MSE = 6.10$. The correctly spelled condition produced shorter total reading times on word n+1 than each of the misspelled conditions (F's > 9.9, $ps < .01$).

To summarise, there were no effects of the critical string on prior fixations. However fixation durations were increasingly longer in the more irregular misspelling conditions for fixations on the critical string and for later measures on word n+1. The misspelled words, especially the very irregular misspellings, were more difficult to process than the correctly spelled words. Previous studies have also shown that misspelled words (Inhoff & Topolski, 1994; Rayner, Pollatsek, & Binder, 1998; Underwood et al., 1988; Zola, 1984), and words which are incorrect in the context of the sentence (Daneman, Reingold, & Davidson, 1995; Ehrlich & Rayner, 1981), produce longer fixation durations.

Table 2.3 *Experiment 1. Mean Landing Positions, Incoming Saccade Extents and Launch Sites. Standard Deviations in Parentheses.*

Experiment 1	Landing position	Saccade extent	Launch site
Correct	4.4 (2.2)	9.1 (3.2)	4.7 (3.4)
High frequency misspelling	4.0 (2.3)	8.9 (2.6)	4.9 (3.4)
Low frequency misspelling	4.0 (2.1)	8.7 (2.6)	4.7 (3.1)
Illegal pronounceable misspelling	3.9 (2.2)	8.8 (3.1)	4.9 (3.5)
Illegal unpronounceable misspelling	4.1 (2.3)	8.8 (2.9)	4.7 (3.2)

[3] In Experiment 1, the F_1 analysis of first pass reading times on word n+1 was based on data from 43 participants due to two participants failing to fixate or having excluded data for word n+1 in at least one of the conditions.

Landing positions. For the first fixation landing position analyses, the space before the critical string was classified as zero and the first letter of the string as one etc. Table 2.3 shows the mean landing positions on the critical string. The mean first fixation landing positions on the critical string were 0.5 to 0.3 characters nearer the word beginning for the misspelled strings compared to the correctly spelled words. There was a significant effect of spelling on the mean first fixation landing position on the critical string, $F_1(4, 176) = 3.08, p = .02, MSE = 0.75$; $F_2(4, 116) = 2.91, p = .02, MSE = 0.57$. Compared to the correctly spelled condition, mean landing positions were significantly nearer the beginning of the word in the high frequency, $F_1(1, 44) = 7.46, p < .01, MSE = 1.6$; $F_2(1, 29) = 15.14, p < .01, MSE = 0.69$, low frequency, $F_1(1, 44) = 8.21, p < .01, MSE = 1.01$; $F_2(1, 29) = 4.97, p = .03, MSE = 1.08$, illegal pronounceable, $F_1(1, 44) = 14, p < .01, MSE = 1.07$; $F_2(1, 29) = 5.7, p = .02, MSE = 1.54$, and the illegal unpronounceable, $F_1(1, 44) = 4.07, p = .05, MSE = 1.3$; $F_2(1, 29) = 6.1, p = .02, MSE = 1.17$, misspelled conditions. No other paired contrasts between the misspelled conditions were significant (t's < 1.4). Figure 2.1 shows the distribution of landing positions for each condition. For all of the conditions, most fixations landed on the preferred viewing position (between the middle and the beginning of the word). Consistent with the difference in mean landing positions, the correctly spelled condition landing position distribution curve is shifted to the right of the misspelled condition curves. Clearly, readers processed the critical string prior to direct fixation and misspellings produced landing positions nearer to the beginning of the critical string compared to when it was spelled correctly.

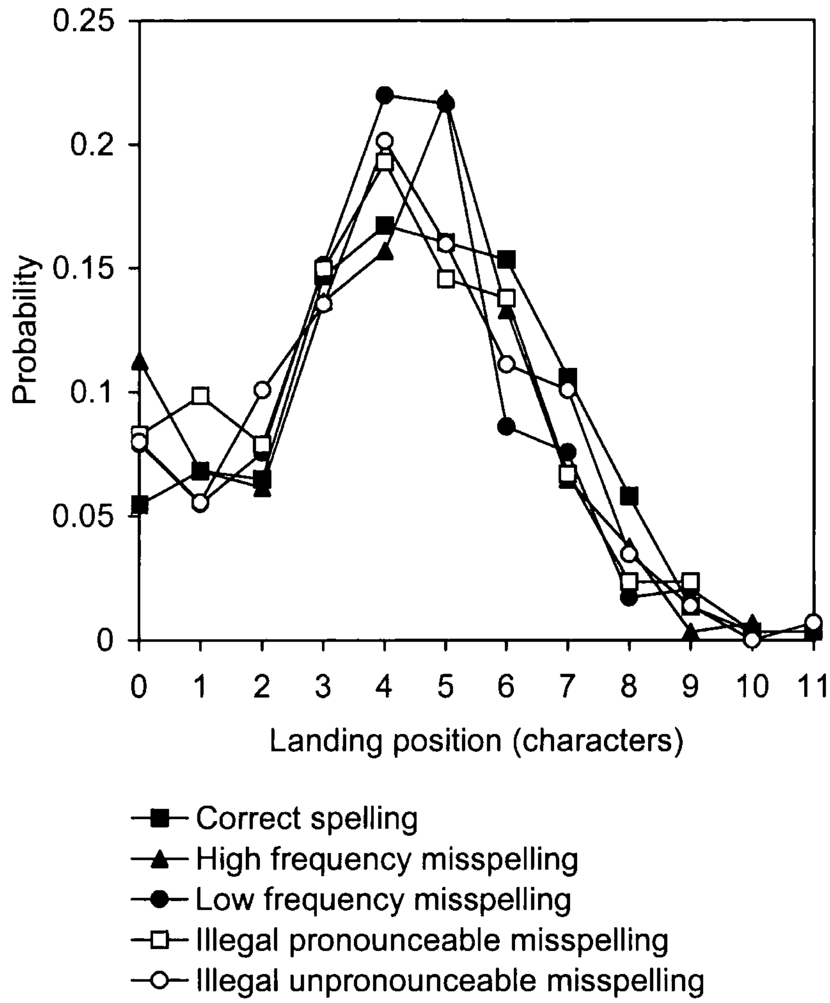

Figure 2.1 Experiment 1. First fixation landing position distributions on the critical string. Landing position zero is the space before the word and landing position one is the first letter of the word.

Incoming saccade extent and launch site. Table 2.3 also shows that the mean saccade lengths into the critical string were numerically longer for the correctly spelled condition than any of the misspelled conditions. However there was no significant effect of spelling on the length of the saccade into the critical string, $F_1(4, 176) = 1.35, p = .253, MSE = 1.06$; $F_2 < 1$. There were also no effects of spelling on the position of the fixation prior to first fixating the critical string (F's < 1) and, in contrast to the means for saccade lengths, Table 2.3 shows no consistent pattern of differences in launch site between the correctly spelled condition and the misspelled conditions.

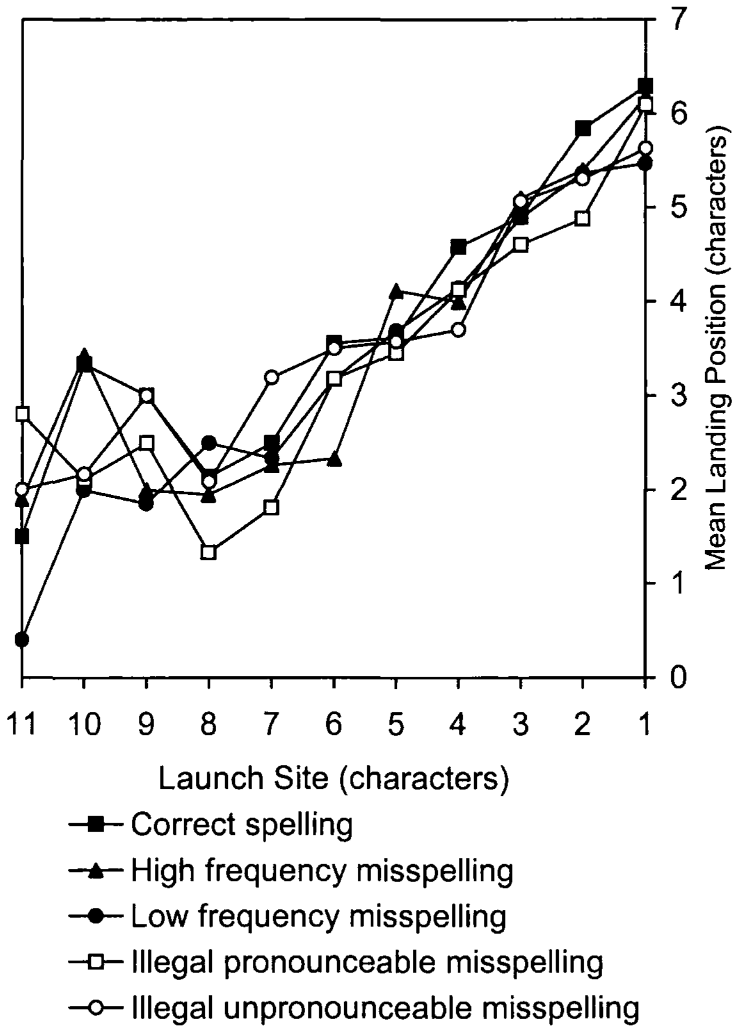

Figure 2.2 Experiment 1. Mean landing position on the critical string for each condition as a function of launch site.

Figure 2.2 shows the mean landing positions for each launch site. At least for near launch sites, mean fixation positions were numerically further into the critical string for correctly spelled words compared to the misspelled critical strings. These results are consistent with an influence of spelling on saccade lengths into the critical string.

Table 2.4 *Experiment 1. Probability of Skipping and Refixating Word n-1 Directly Before Fixating the Critical String. Probability of Skipping Word n-1 Directly Before Fixating the Critical String when Trials in Which Regressions Were Made From Word n-1 Were Considered Separately (Skip (exc. regressions)). Probability of Skipping, Making a Single Fixation and Refixating (≥Two) the Critical String on First Pass. Standard Deviations in Parentheses.*

Experiment 1	Word n-1 fixation probabilities			Critical string fixation probabilities		
	Skip	Skip (exc. regressions)	Refixate	Skip	Single	≥Two
Correct	0.17 (0.18)	0.09 (0.11)	0.08 (0.11)	0.03 (0.09)	0.72 (0.21)	0.25 (0.2)
High frequency misspelling	0.23 (0.21)	0.17 (0.19)	0.08 (0.11)	0.02 (0.06)	0.64 (0.21)	0.34 (0.22)
Low frequency misspelling	0.18 (0.16)	0.11 (0.12)	0.1 (0.13)	0.02 (0.06)	0.56 (0.25)	0.42 (0.26)
Illegal pronounceable misspelling	0.22 (0.21)	0.14 (0.16)	0.08 (0.12)	0.01 (0.04)	0.58 (0.25)	0.41 (0.25)
Illegal unpronounceable misspelling	0.23 (0.21)	0.16 (0.17)	0.09 (0.12)	0.02 (0.07)	0.55 (0.22)	0.43 (0.2)

Table 2.4[4] shows the probability of skipping word n-1 before fixating the critical string. However, some of the word skips were associated with trials in which word n-1 was fixated, a regression was made from word n-1 and word n-1 was subsequently skipped, these trials may have provided greater preview of the critical string compared to those cases in which word n-1 was not fixated on first pass. Consequently, the probability of skipping word n-1 before fixating the critical string was also calculated when those cases in which first pass regressions were made from word n-1 were considered separately (such that the total probabilities were composed

[4] Throughout the thesis, standard deviations for probabilities are calculated across the probabilities for each participant.

of skips, fixations, and regression cases). For both these data sets, the probability of skipping word n-1 was numerically greater for the misspelled conditions than for the correctly spelled condition. When all of the skipping cases were considered, there was no effect of spelling on the probability of skipping the previous word, $F_1(4, 176) = 2.05, p = .09, MSE = 202$; $F_2(4, 116) = 1.84, p = .126, MSE = 219$. When those trials in which regressions were made from word n-1 were considered separately, there was a significant main effect of spelling on the probability of skipping word n-1, $F_1(3.2, 141.8) = 3.55, p = .01, MSE = 202$; $F_2(4, 116) = 3.26, p = .01, MSE = 154$, and word n-1 was less likely to be skipped in the correctly spelled condition than the high frequency, $F_1(1, 44) = 10.5, p < .01, MSE = 328$; $F_2 (1, 29) = 11.93, p < .01, MSE = 225$, and illegal unpronounceable $F_1(1, 44) = 9.07, p < .01, MSE = 261$; $F_2 (1, 29) = 4.83, p = .04, MSE = 447$, misspelled conditions. There was no significant difference for the low frequency misspelling condition (F's < 1.2) and a significant difference across participants, $F_1(1, 44) = 5.69, p = .02, MSE = 172$, but not items, $F_2 (1, 29) = 2.33, p = .138, MSE = 312$, for the illegal pronounceable misspelling condition. Table 2.4 also shows the probability of refixating word n-1. There were no effects of spelling on the probability of refixating word n-1 directly before fixating the critical string (F's < 1). The finding that spelling influenced the probability of skipping the previous word suggests that the misspellings may have attracted saccades from distant launch sites. Figure 2.3 shows the distribution of launch sites for each condition. Consistent with the greater probability of skipping word n-1 in the high frequency and illegal unpronounceable misspelled conditions, there are slightly more saccades launched from seven or more characters from the critical string in these conditions compared to the correctly spelled condition.

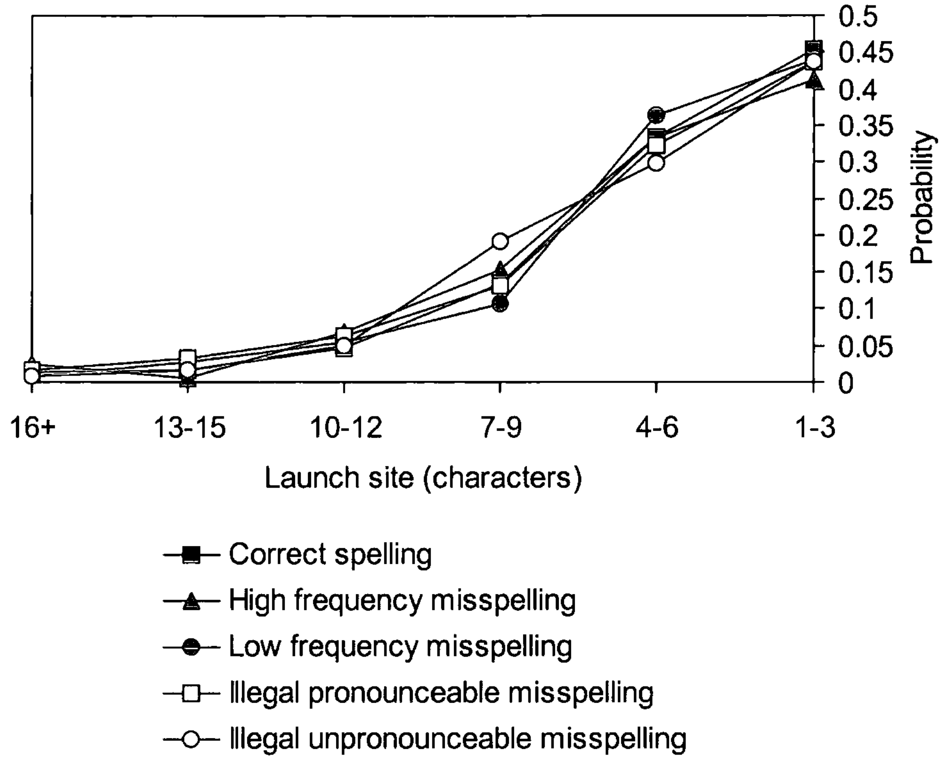

Figure 2.3 Experiment 1. Launch site distributions for saccades directed to the critical string.

Section 1.3.1 explained that landing position effects must be accounted for by either or both differences in saccade length or launch site. Although there were no significant effects of incoming saccade extent or launch site, the results suggest that differences in both these factors may have contributed to the landing position effect. That is, non-significant differences in the mean incoming saccade extent and differences in the probability of skipping word n-1 may both have influenced first fixation positions on the critical string.

Table 2.5 *Experiment 1. For Cases in Which the Critical String was Fixated on First Pass: Probability of Refixating the Critical String. Probability of First Refixating to the Left of the Initial Fixation on the Critical String. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 1	Correct	Misspelled			
		High frequency	Low frequency	Illegal pronounceable	Illegal un-pronounceable
Refixation probability	0.26 (0.2)	0.35 (0.22)	0.43 (0.26)	0.42 (0.25)	0.43 (0.21)
Leftward refixation probability	0.34 (0.36)	0.34 (0.34)	0.49 (0.37)	0.46 (0.4)	0.56 (0.35)
Rightward saccade length	5.0 (2.2)	5.0 (2.1)	4.8 (2.1)	5.2 (2.0)	5.3 (2.0)
Rightward landing position	7.0 (2.0)	6.8 (1.7)	6.7 (1.5)	7.0 (2.0)	7.2 (2.1)

Refixations. Table 2.4 shows the overall probabilities of refixating the critical string. Table 2.5 shows the probability of refixating the critical string for those cases in which a first pass fixation was made on the critical string. There was a significant effect of spelling on the probability of refixating the critical string on first pass, $F_1(4, 176) = 7.65, p < .01, MSE = 330$; $F_2(4, 116) = 6.66, p < .01, MSE = 291$. The correctly spelled condition was significantly less likely to be refixated than any of the four misspelled conditions (F's > 4.2, $ps < .05$). Similar to the reading time measures, these results suggest that the misspelled words were more difficult to process than the correctly spelled words because they produced more first pass refixations on the critical string.

Table 2.5 shows the probability of making a refixation to the left of the initial fixation on the critical string for those trials in which multiple first pass fixations occurred on the critical string. There was a significant effect of spelling on the probability of making a refixation to the left of the initial fixation[5], $F_1(4, 104) = 2.77$, $p = .03$, $MSE = 1003$; $F_2(4, 88) = 5.91$, $p < .01$, $MSE = 666$. Compared to the correctly spelled condition, refixations were more likely to be to the left of the initial fixation in the low frequency, $F_1(1, 26) = 5.81$, $p = .02$, $MSE = 2308$; $F_2(1, 22) = 7.6$, $p = .01$, $MSE = 1434$, and the illegal unpronounceable, $F_1(1, 26) = 8.03$, $p < .01$, $MSE = 2134$; $F_2(1, 22) = 18.02$, $p < .01$, $MSE = 1255$, misspelled conditions. For the illegal pronounceable misspelled condition the effect was significant across participants but not items, $F_1(1, 26) = 4.27$, $p = .05$, $MSE = 1412$; $F_2(1, 22) = 2.82$, $p = .107$, $MSE = 1490$. There was no significant difference in the probability of refixating to the left of the initial fixation for the correct and high frequency misspelled words, $F_1(1, 26) = 1.27$, $p = .27$, $MSE = 1848$; $F_2 < 1$. The results suggest that the more irregular misspelled items were more likely to produce regressive refixations than the correctly spelled condition.

Only 11 participants and 13 items produced rightward refixation saccades on the critical string in all of the conditions. Consequently, there was insufficient data to examine whether spelling influenced rightward refixation saccade lengths and fixation positions.

2.2.3: Discussion

In accordance with previous evidence, the results clearly show that most fixations land left of the word centre on the preferred viewing position (Dunn-Rankin, 1978; McConkie et al., 1988; Rayner, 1979) and that more distant launch sites are associated with landing positions nearer the beginning of words (Hyönä, 1995; McConkie et al., 1994; McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner et al., 1996). These results support the wealth of evidence outlined in Section 1.3.1 showing that word length and launch site are very important factors in influencing where words are first fixated in reading. However the results

[5] In Experiment 1, for the analyses of the probability of refixating to the left, only participants and items that produced refixations in all of the conditions were included. Consequently the F_1 analysis was based on 27 participants and the F_2 analysis was based on 23 items.

also show that preprocessing beyond the level of word length can also influence where words are fixated.

First fixation positions were significantly nearer the word beginning for misspelled compared to correctly spelled words. The results of the three orthographically irregular misspelled conditions (illegal unpronounceable, illegal pronounceable, low frequency) suggest that non-foveal processing at least at the level of orthographic regularity can influence where words are fixated. The results are consistent with sentence reading studies undertaken in languages other than English that have shown that word initial orthographic regularity influences where words are first fixated (Hyönä, 1995; Radach et al., 2003; Vonk et al., 2000).

As detailed in Section 1.3.3, a number of possible explanations have been proposed to account for how preprocessing of orthography might influence landing positions. The fact that saccade lengths were numerically shorter for the misspelled conditions compared to the correctly spelled condition is consistent with both attraction (Beauvillain et al., 1996; Findlay & Walker, 1999; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) and general linguistic processing (Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992) based explanations. Consistent with the attraction based explanations, word n-1 was more likely to be skipped before fixating the critical string for the high frequency and illegal unpronounceable misspelled conditions compared to the correctly spelled condition. This result suggests that saccades might be attracted from distant launch sites on the basis of some types of non-foveal features (see Section 1.3.3). Since word n-1 was always five or six letters long, then if word n-1 was more likely to be skipped then this means that saccades were more likely to be launched from six or more characters away. Therefore the results suggest that for the high frequency and illegal unpronounceable misspelled conditions, saccades may have been attracted from distant launch sites such that word n-1 was more likely to be skipped in these conditions compared to the correctly spelled word.

As explained in Section 1.3.1, differences in launch site can produce differences in landing position. According to the range effect, saccades launched from distant launch sites tend to land nearer to the beginning of words than those launched from near positions (McConkie et al., 1988). Therefore, for those conditions in which word n-1 was more likely to be skipped, saccades should have landed nearer the beginning of the critical string. In line with this, Figure 2.1 shows that the high frequency and illegal unpronounceable misspelled conditions produce numerically more fixations at the very beginning of the critical string compared to the correctly spelled condition. Note that Hyönä (1995) showed a similar pattern of results. That is, irregular beginning words produced more fixations on the space before the word, and word n-1 was numerically more likely to be skipped, compared to regular beginning words.

As explained in Section 1.3.3, Hyönä (1995) suggested that irregular beginning words might induce processing difficulty which then changes the target of the saccade to the space before the word. If this was the case, there should be a distinct peak in the number of fixations landing on the space before the word. In order to investigate this possibility the landing position distribution was re-calculated to include the critical string and the final two letters of word n-1, shown in Figure 2.4. No more than two letters from word n-1 were included because this would have considerably reduced the amount of data contributing to landing positions on the critical string. Figure 2.4 shows that, especially for the illegal unpronounceable condition, the increase in fixations on the space before the word is not an isolated peak, instead it may be interpreted as part of the decrease in the proportion of fixations that land near the end of word n-1. These descriptive data can not definitively show that saccades are not targeted specifically to the space before the word. However, the results are consistent with the notion that, when more saccades are launched from distant launch sites, fixations are generally more likely to land nearer the beginning of the word, rather than being targeted directly to the space before the word.

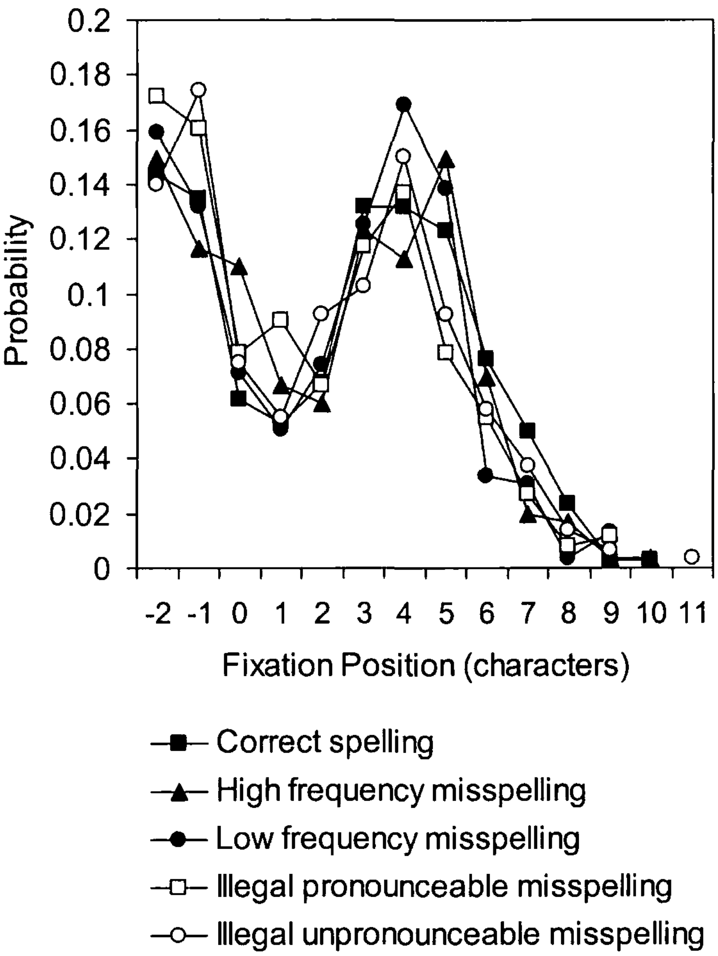

Figure 2.4 Experiment 1. Landing position distributions for first fixation positions on the final two characters of word n-1 (characters –2 and –1), the space between word n-1 and the critical string (character 0) and fixation positions on the critical string (character 1 onwards).

As explained above, the word skipping data suggest that the high frequency misspelling and illegal unpronounceable landing position results might be associated with saccades attracted from distant launch sites. Other studies have also shown that the characteristics of a word can influence the probability of skipping the previous word. In support of the results of Experiment 1, Hyönä and Bertram (in press a) showed that, in some cases, compound words with low frequency initial constituents increased the probability of skipping the previous word compared to words with high frequency initial constituents. However, note that in contrast to these effects, Pynte et al. (in press) reported that irregular misspellings reduce, not increase, the probability of skipping the previous word. Therefore, although the skipping result shown in Experiment 1 supports the attraction based explanations, the result must be treated with caution until it is found to be reliable in other studies. Consequently, the results of Experiment 1 can not clearly distinguish between the attraction and general linguistic processing explanations for the landing position results. In addition, the landing position effects might be interpreted as being due to either linguistic (e.g. Hyönä & Pollatsek, 1998) or visual (Findlay & Walker, 1999; Reichle et al., in press) non-foveal preprocessing. Chapters 4 and 5 therefore investigate these possible explanations for the influences of orthography on fixation positions.

In contrast to the initial landing position results for the three orthographically irregular misspelled conditions, the results for the high frequency misspelled condition are more difficult to account for. First fixation landing positions were significantly nearer the word beginning for the high frequency misspelled condition compared to the correctly spelled condition. There were no differences between initial trigram frequencies in the correct and high frequency misspelling conditions, and the position in the word at which the high frequency misspelled words became illegal was uncontrolled. Therefore letter sequences up to at least the first four letters of the high frequency misspelled strings had to be preprocessed in order for the word initial letter sequence to be detected as irregular. Importantly, although the string would have to be processed up to at least the fourth letter, shorter infrequent or illegal letter sequences may have been detected (for example "*quc*" in "*equcation*"). Nevertheless, this result is surprising because Beauvillain and Doré (1998) showed that the letter sequence frequency of the second and third letters of a letter string did not influence fixation positions. Furthermore, Underwood et al. (1988) misspelled the third letters of words and reported no significant effect of spelling on landing positions. The high frequency misspelling result suggests that letter sequences that are positioned further into the word than those tested by Beauvillain and Doré and Underwood et al. can influence fixation positions.

The high frequency misspelling result is even more surprising because, as explained above, it appears to be at least partly determined by saccades being attracted from distant launch sites. That is, word n-1 is more likely to be skipped when there is a high frequency misspelling than when the critical string is spelled correctly. Such a suggestion implies that processing beyond the level of the orthographic regularity of the word initial trigram can be undertaken on text presented more than one word from fixation. Text further than one word from fixation is beyond, or certainly towards the far edge of, the region of text from which letter information can be processed

(McConkie & Rayner, 1975; Rayner, 1975b). Consequently, there is some doubt over whether the high frequency misspellings really could have been preprocessed from distant launch sites, attracted saccades towards them and consequently influenced initial fixation positions on the high frequency misspelled words.

There are at least three possible explanations for the high frequency misspelling landing position result. First, the high frequency misspelled strings, or letter sequences within these strings, might have been identified as illegal and this may have influenced saccade programming to those strings. Secondly, the stimuli were chosen primarily on the basis of token, rather than type, frequency. Although there were no significant differences in type frequency, the high frequency misspelling condition had initial trigrams with a greater range and variation (range: 1-679, SD = 115) than the correctly spelled condition (range: 8 - 421, SD = 88) and therefore differences in type frequency (i.e. informativeness) might have influenced fixation positions. This suggestion is consistent with the findings of Underwood and colleagues who suggested that the distribution of informative letter sequences within words can influence landing positions (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987). However other studies have not shown such effects (Beauvillain et al., 1996; Hyönä, 1995; Rayner & Morris, 1992; Underwood et al., 1989). The third possibility is that, given that the high frequency misspelling result was a surprising finding in relation to previous research, it may be spurious.

Experiment 1 also yielded interesting results regarding the nature of refixations. As explained in Section 1.4, there is a debate as to whether visual or linguistic factors determine the programming of refixations. O'Regan (1990) argued that the locations of refixations are determined by the position of the first fixation on a word in relation to the word length. However in Experiment 1 more refixations were made to the left of the initial fixation position for misspelled compared to correctly spelled critical strings. In support of previous studies (Pynte, 1996, 2000; Pynte et al., 1991; Underwood et al., 1988; Underwood et al., 1987) the results suggest that the characteristics of a word influence the location of refixations. However, in the present experiment the critical strings were misspelled and therefore it is possible that processes unusual to normal reading, such as problem solving to identify the foveal misspelled words, may have influenced these effects.

Experiment 1 also provided a strong test of the possibility that the characteristics of a word can be preprocessed such that they influence previous fixations. There was no evidence of such "parafoveal-on-foveal effects" on prior fixation durations. Previous studies using artificial tasks (Kennedy, 1998, 2000b; Kennedy et al., in press; Murray, 1998; Murray & Rowan, 1998), and sentence reading studies (Inhoff, Radach et al., 2000; Inhoff, Starr et al., 2000; Pynte et al., 2003; Kennedy et al., 2002; Underwood et al., 2000; Starr & Inhoff, in press) have suggested that the characteristics of a word can influence fixation times on the previous word. In contrast, in Experiment 1 there were no effects of the spelling of the critical string on the fixation duration prior to fixating the critical string, even when the prior fixation was three or less characters from the beginning of the critical string. Furthermore, the landing position effects show that the initial letter sequences were processed before the critical strings were fixated, and yet there was no effect of the initial letter sequence on the prior fixation duration. Another way in which the characteristics of a word might produce parafoveal-on-foveal effects is to influence prior fixation probabilities. There were no effects of the spelling of the critical string on the probability of refixating word n-1 directly before fixating the critical string, but there were effects on the probability of skipping word n-1. However, as noted above, the skipping results are in the opposite direction to those reported by Pynte et al. (in press). Therefore, the absence of parafoveal-on-foveal effects on fixation durations suggests that there is no strong evidence for parallel processing of words such that the characteristics of words can influence prior fixation durations. In addition, the evidence for parafoveal-on-foveal effects on prior fixation probabilities is inconsistent and so more data is required to investigate this issue.

2.3: Conclusions

The aim of Experiment 1 was to investigate whether, and what kinds, of non-foveal preprocessing can influence fixation positions in reading. Most importantly, the results show that letter strings with orthographically irregular initial letter sequences produce initial fixation positions nearer the word beginning than those with orthographically regular initial letter sequences. Importantly, this is the first study to find an effect of orthographic regularity on landing positions for English language sentences. These results are particularly striking since current models of eye movements in reading make no attempt to account for the influence of orthography on either first fixation or refixation positions (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990). Furthermore, in support of serial attention shift accounts of eye movements in reading (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press) and in contrast to parallel attention allocation explanations (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980), the results show no evidence for parafoveal-on-foveal effects on prior fixation durations.

Chapter 3

Absence of Lexical Influences on Fixation Positions

In Experiment 1 (Chapter 2) misspelled words with frequent initial trigrams produced first fixation landing positions significantly nearer the word beginning compared to the correctly spelled words. The results suggested that preprocessing of the critical string beyond the initial trigram influenced where words were first fixated. The discussion of Experiment 1 (Section 2.2.3) explained that the difference in landing positions for the high frequency misspellings was associated with saccades being attracted from distant launch sites. This was a surprising finding because in order to detect the high frequency misspellings, at least the initial four letters of the critical strings would have to be processed. On the basis of previous evidence it seems unlikely that such high level preprocessing would be possible from distant launch sites (McConkie & Rayner, 1975; Rayner, 1975b). In addition, the high frequency misspelling result seems inconsistent with previous studies which have found no lexical influences on fixation positions (Beauvillain et al., 1996; Hyönä, 1995; Rayner & Morris, 1992; Underwood et al., 1989).

Due to the surprising nature of the high frequency misspelling result in Experiment 1, Experiments 2 and 3 were designed to provide stronger tests of whether such extensive preprocessing can influence initial landing positions. Experiment 2 (Section 3.1) tests the first possible explanation for the high frequency misspelling result (proposed in Section 2.2.3) which is that the letter strings were preprocessed as illegal and consequently influenced saccade programming. Experiment 3 (Section 3.2) tests the second possible explanation (also proposed in Section 2.2.3) which is that the results might be explained by differences in the distribution of informativeness for word recognition within the letter strings. That is, whether the word initial letters generate few or many possible lexical candidates.

A number of studies have specifically suggested that preprocessing of possible lexical candidates can produce parafoveal-on-foveal effects (Kennedy, 1998, 2000b; Kennedy et al., 2002; Pynte et al., in press) (see Section 1.5). Experiments 2 and 3 directly manipulate the lexical, rather than orthographic, properties of word initial letters. Therefore, if parafoveal-on-foveal effects based on lexical candidate generation are robust then Experiments 2 and 3 should show such effects. As in Experiment 1, two types of parafoveal-on-foveal effects were investigated. That is, whether the characteristics of the critical string influence fixation durations or fixation probabilities before the critical string is fixated.

3.1: Experiment 2

In Experiment 1 there were no significant differences in initial trigram frequencies between the correct and the high frequency misspelling condition, however the letter string beginnings were different (e.g. *agr* compared to *acr* initial trigrams). In the present experiment, in two of the misspelled conditions the letter at which the word became illegal was misspelled (hence the initial letters were identical) or the second letter was misspelled (as in Experiment 1). In Experiment 1 the position in the word at which the initial letters became illegal was uncontrolled, ranging from the fourth letter (e.g. *equcation*) to the sixth letter (e.g. *shandards*). In the present experiment this was manipulated, the words became illegal at either the fourth or fifth letter.

If the effects in Experiment 1 were due to detection of illegal letter strings then landing position effects should occur for all four of the misspelled conditions in Experiment 2. If the effects only occur when the second letter is misspelled then the effects may be due to lexical candidate generation processes associated with the word initial letters, for example related to word length, rather than abstract processing of the whole letter string. If there are only landing position effects for the words that become unique earlier in the word (at the fourth rather than the fifth letter) then again the effects might be due to processing of just the word initial letters rather than letters further into the word. Alternatively, if the third possible explanation suggested in Section 2.2.3 is correct, that is, that the high frequency misspelling effect in Experiment 1 is spurious, then there should be no effect of spelling on fixation positions in Experiment 2.

3.1.1: Method

Participants. Forty members of the University of Durham community participated in the experiment. All of the participants were native English speakers with normal or corrected to normal vision. The participants were paid to participate and all were naïve in relation to the purpose of the experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Materials and Design. Word frequencies and case-insensitive n-gram frequencies were calculated using the CELEX English word form corpus (Baayen, et al, 1995). All of the critical strings were eight or nine characters long (M = 8.5, SD = 0.5) and the mean word frequency in counts per million was 14 (range: 0 – 68, SD = 18). There were five conditions which were manipulated within participants and items. In the baseline condition the critical string was spelled correctly (e.g. *practical*). There were four misspelled conditions, for brevity these will be given abbreviations which refer to the position of the misspelling ("M") and the uniqueness point at which the initial letters become illegal ("UP"). In the M2UP4 condition the second letter was misspelled and the string became illegal on the fourth letter (e.g. *phactical*). In the M2UP5 condition the second letter was misspelled and the string became illegal on the fourth letter (e.g. *plactical*). In the M4UP4 condition the fourth letter was misspelled and the string became illegal on the fourth letter (e.g. *praltical*). In the M5UP5 condition the fifth letter was misspelled and the string became illegal on the fifth letter (e.g. *prachical*). Where possible, the misspelled letters in the M4UP4 and M5UP5 condition matched the original consonant-vowel structure (eight exceptions). Type frequency is the total number of words that contain a particular letter sequence. Token frequency is the sum of the frequencies of the words that contain a particular letter sequence. Position specific n-gram token frequencies were calculated in counts per 17.9 million. Type frequencies followed similar patterns but were not so closely controlled as token frequencies. However, any effects of type frequency would reflect differences in candidate generation processes. Importantly, the careful control of token frequencies ensures that any effects can not be due to differences in the familiarity of the word initial letter sequences.

For the two misspelled conditions in which the second letter was misspelled there were no differences in initial letter sequence n-grams between these and the misspelled conditions. There were no differences in initial quadrigram frequency between the correct (M = 1794, SD = 1798) and M2UP5 conditions (M = 2517, SD = 3107), t (39) = 1.3, p =.195. There were no differences in initial trigram frequency between the correct (M = 125345, SD = 17832) and the M2UP4 (M = 12943, SD = 14107) or the M2UP5 conditions (M = 16355, SD = 21573) (ts < 1). There were also no differences in initial bigram frequency between the correct (M = 118937, SD = 117369) and M2UP4 (M = 94137, SD = 139741) or the M2UP5 (M = 131533, SD = 143681) conditions (ts < 1). There were no differences in monogram frequency for the second letter between the correct (M = 1120167, SD = 933941) and M2UP4 (M = 1185577, SD = 919403) or M2UP5 (M = 1345060, SD = 982655) (ts < 1.4) conditions.

For the two misspelled conditions in which the letter at which the word became illegal (fourth or fifth character) was misspelled, the initial n-gram frequencies were obviously the same as the correctly spelled condition. There were no differences in monogram frequency for the fourth letter between the correct (M = 582509, SD = 350273) and M4UP4 (M = 522972, SD = 263515) condition (t < 1). There were no differences in monogram frequency for the fifth letter between the correct (M = 398238, SD = 240714) and M5UP5 (M = 424912, SD = 282598) condition (t < 1).

The 40 critical strings were embedded in identical sentence frames for each condition. Each of the sentences was no longer than one line of text (78 characters) and the critical string appeared approximately in the middle of the sentence. The words before and after the critical string were either five or six letters long and had medium to high frequencies. Most of the sentences included context relevant to the critical word at the beginning of the sentence. See Appendix B for a list of experimental sentences and critical strings.

Five lists of 144 items were constructed and eight participants were randomly allocated to each list. Each list included 40 experimental items of which 8 items were from each of the five misspelling conditions. The conditions were rotated following a Latin square design. There were 16 misspelled filler items with misspellings in a variety of word lengths and in a variety of positions within the word and the sentence. There were also 88 filler items that were spelled correctly. Therefore of the 144 items 48 contained a misspelling. Forty-eight of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences. The sentences were presented in a fixed random order with eight filler sentences at the beginning.

Procedure. The experimental procedure was the same as in Experiment 1. The entire experiment lasted approximately 30 minutes and participants were given one break.

Analyses. The analyses were the same as in Experiment 1. Two percent of trials were excluded due to either no first pass fixations on the sentence prior to word n-1 or tracker loss or blinks on first pass reading of word n-1 or the critical string.

3.1.2: Results

The results were analysed using the same measures as used in Experiment 1. Repeated measures analyses of variance (ANOVAs) were undertaken across the five spelling conditions, with participants (F_1) and items (F_2) as random variables. If there were significant main effects across both participants and items then two further analyses were undertaken. First, simple effects were computed comparing the correctly spelled condition with each of the misspelled conditions. Secondly, the four misspelled conditions were analysed using a 2 (spelling position: second character or the point at which the word becomes illegal) X 2 (point of illegality: fourth or fifth character) repeated measures ANOVA. Paired samples t-tests were undertaken across both participants (t_1) and items (t_2) for comparisons between pairs of variables. The mean error rate on the comprehension questions was four percent indicating that the participants properly read and understood the sentences.

Table 3.1 *Experiment 2. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Standard Deviations in Parentheses.*

Experiment 2		Word n-1		Fixation n-1		
		FF	GD	All	n-1	≤3
Correct		271 (76)	296 (97)	261 (75)	269 (74)	264 (63)
Second letter misspelled	Illegal at 4th (M2UP4)	260 (61)	303 (111)	258 (73)	260 (70)	263 (79)
	Illegal at 5th (M2UP5)	272 (80)	306 (113)	257 (78)	263 (70)	261 (79)
Letter at point of illegality misspelled	Illegal at 4th (M4UP4)	276 (87)	303 (114)	269 (88)	271 (90)	265 (80)
	Illegal at 5th (M5UP5)	270 (86)	292 (105)	264 (75)	269 (79)	265 (88)

Parafoveal-on-foveal effects. Table 3.1 shows the mean fixation durations prior to fixating the critical string. There were no significant effects of spelling on first fixation, F_1 (4, 156) = 1.58, p = .182, MSE = 885; F_2 < 1.1, or gaze duration F_1 (4, 156) = 1.35, p = .254, MSE = 1301; F_2 < 1, for word n-1. The probabilities of refixating word n-1 on first pass were 0.1 for the correctly spelled, 0.16 for the M2UP4, 0.13 for the M2UP5, 0.1 for the M4UP4 and 0.08 for the M5UP5 condition, however these numerical differences were not significant, F_1 (3.3, 127.9) = 2.21, p = .084, MSE = 157; F_2 (4, 156) = 2.25, p = .067, MSE = 135. The probabilities of skipping word n-1 on first pass were 0.11 for the correctly spelled, 0.13 for the M2UP4, 0.13 for the M2UP5, 0.12 for the M4UP4 and 0.12 for the M5UP5 condition, but these differences were not significant (F's < 1). There were no significant effects of spelling on the duration of the fixation prior to first fixating the critical string for all of the data, for saccades launched from word n-1 and for saccades launched from three or less characters from the critical string (F's < 1.2). Therefore the results show no evidence of parafoveal-on-foveal effects on either prior fixation durations or fixation probabilities.

Table 3.2 *Experiment 2. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String and Word n+1. Fixation Duration After Leaving the Critical String (Fix. n+1). Standard Deviations in Parentheses.*

Experiment 2		Critical string			Fix.	Word n+1		
		FF	GD	TT	n+1	FF	GD	TT
Correct		288 (83)	357 (147)	417 (229)	265 (79)	268 (81)	283 (86)	319 (149)
Second letter misspelled	Illegal at 4th (M2UP4)	323 (106)	475 (264)	670 (465)	290 (118)	302 (121)	325 (143)	386 (209)
	Illegal at 5th (M2UP5)	327 (121)	451 (254)	644 (423)	285 (114)	294 (121)	305 (134)	391 (227)
Letter at point of illegality misspelled	Illegal at 4th (M4UP4)	335 (159)	517 (333)	695 (449)	282 (111)	292 (114)	320 (147)	390 (204)
	Illegal at 5th (M5UP5)	325 (145)	478 (291)	649 (434)	272 (100)	279 (106)	294 (120)	368 (202)

Reading time measures. Table 3.2 shows the mean reading time measures on the critical string and word n+1. For the critical string there were significant effects of spelling on first fixation, F_1 (3.2,124.9) = 7.46, $p < .01$, $MSE = 2256$; F_2 (4, 156) = 5.95, $p < .01$, $MSE = 2206$, gaze duration, F_1 (3.1,119.6) = 14.12, $p < .01$, $MSE = 12897$; F_2 (4, 156) = 12.81, $p < .01$, $MSE = 10748$, and total time, F_1 (4, 156) = 26.62, $p < .01$, $MSE = 18869$; F_2 (4, 156) = 24.08, $p < .01$, $MSE = 20509$. For all measures reading times were longer on the four misspelled critical strings compared to the correctly spelled critical string (F's > 9.9, ps < .01). Therefore consistent with Experiment 1 reading times are longer on words with a high frequency misspelling compared to correctly spelled words. In addition, the results are consistent with previous studies showing that misspelled words produce longer reading times than correctly spelled words (Inhoff & Topolski, 1994; Rayner, Pollatsek et al., 1998; Underwood et al., 1988; Zola, 1984).

For the first fixation duration on the critical string there were no main effects of misspelling position or point of illegality and no interaction (F's < 1.2). Gaze durations were significantly longer on the critical string when it was misspelled at the point of illegality compared to the second letter, F_1 (1, 39) = 4.35, $p = .04$, $MSE = 10164$; F_2 (1, 39) = 4.02, $p = .05$, and gaze durations tended to be longer when the critical string became illegal at the fourth, compared to the fifth, letter and this was significant across participants but not items, F_1 (1, 39) = 5.97, p = .02, MSE = 6759; F_2 (1, 39) = 3.65, p = .06, there was also no interaction between misspelling position and the point of illegality (F's < 1). For the total time on the critical string there were no main effects of misspelling position (F's < 1) or point of illegality, F_1 (1, 39) = 2.62, p = .114, MSE = 15885; F_2 (1, 39) = 2.46, p = .125, and no interaction (F's < 1). Therefore the nature of the misspelling influenced gaze durations but not first fixations or total time on the critical string. The gaze durations suggest that the misspelled words were more difficult to process when the fourth or fifth letters were misspelled compared to the second letter. In addition, the words were more difficult to process if the fourth, rather than the fifth, letter was misspelled.

Table 3.2 shows the mean reading times after leaving the critical string. There were no reliable effects of spelling on the fixation after leaving the critical string, F_1 (4, 156) = 3.11, p = .017, MSE = 1329; F_2 (4, 156) = 2.25, p = .066, MSE = 1809, or on first fixation durations on word n+1, F_1 (4, 156) = 2.25, p = .066, MSE = 1904; F_2 (4, 156) = 3.37, p = .011, MSE = 2217. However gaze durations on word n+1 were significantly longer when the critical string was misspelled, F_1 (4, 156) = 4.81, p < .01, MSE = 1952; F_2 (2.8,110.2) = 3.66, p = .02, MSE = 5217. Simple effects showed that gaze durations on word n+1 were significantly longer when the critical string was misspelled in the M2UP4, F_1 (1, 39) = 9.02, p < .01, MSE = 4602; F_2 (1, 39) = 11.35, p = .02, MSE = 6044, and M4UP4, F_1 (1, 39) = 10.33, p < .01, MSE = 4369; F_2 (1, 39) = 6.97, p = .01, MSE = 9420, conditions. Although gaze durations were numerically longer on word n+1 in the M2UP5 condition compared to the correct condition, this difference was significant across items F_2 (1, 39) = 5.43, p = .03, MSE = 5753, but not participants, F_1 (1, 39) = 1.45, p = .236, MSE = 5049. Furthermore, there was no difference between the correct and M5UP5 condition, F_1 < 1; F_2 (1, 39) = 1.61, p = .211, MSE = 2792. Further analyses of the effect of misspellings showed that gaze durations on word n+1 were longer when the strings became illegal on the fourth compared to the fifth letter, F_1 (1, 39) = 10.12, p < .01, MSE = 2160; F_2 (1, 39) = 4.32, p = .04, MSE = 4359, there were no effects of misspelling position and no interaction (F's < 1). There were also effects of spelling on the total time spent on word n+1, F_1 (4, 156) = 5.87, p < .01, MSE = 4979; F_2 (3.3,130.2) = 4.87, p < .01, MSE = 8106. However in contrast to the effects on gaze duration, simple effects showed that total time on word n+1 were longer for all types of misspelling of the critical string compared to the correctly spelled condition (F's > 8.2, ps < .01). There were no effects of the position of misspelling (F's < 1), point of illegality (F's < 1) and no interaction, F_1 (1, 39) = 1.98, p = .167, MSE = 4743; F_2 (1.39) = 1.42, p = .24, MSE = 5361, between these factors for total time on word n+1.

Therefore, there were no reliable spillover effects for early measures (fixation duration after leaving the critical string and first fixation duration on word n+1). Similar to reading time measures on the critical string, gaze durations on word n+1 were longer when the critical string became illegal at the fourth letter compared to when it became illegal at the fifth letter and compared to when the critical string was spelled correctly. Total time on word n+1 simply showed longer total reading times on word n+1 when the critical string was misspelled compared to when it was spelled correctly. Therefore there was evidence of continued effects of the misspellings for later reading time measures on the following word, especially when the fourth letter of the word was misspelled.

In general, the reading time measures correspond to the effects for the high frequency misspelling condition in Experiment 1. That is, reading time measures on the critical string were longer when it was misspelled. In addition, there were longer total reading times on word n+1 when the critical string was misspelled compared to when it was spelled correctly.

Table 3.3 *Experiment 2. Mean Landing Positions, Incoming Saccade Extents and Launch Sites. Standard Deviations in Parentheses.*

Experiment 2		Landing position	Saccade extent	Launch site
Correct		3.6 (2.0)	8.1 (2.4)	4.5 (2.9)
Second letter misspelled	Illegal at 4th (M2UP4)	3.6 (2.0)	7.9 (2.3)	4.3 (2.8)
	Illegal at 5th (M2UP5)	3.6 (2.0)	8.3 (3.0)	4.7 (3.2)
Letter at point of illegality misspelled	Illegal at 4th (M4UP4)	3.6 (2.2)	8.0 (2.4)	4.4 (2.7)
	Illegal at 5th (M5UP5)	3.6 (2.0)	8.2 (2.4)	4.6 (2.8)

Landing position. Table 3.3 shows the mean first fixation positions on the critical string in each of the conditions. There were no significant effects of spelling on landing position (*F*'s < 1). Figure 3.1 shows the distribution of landing positions for each of the conditions, note that most fixations landed on the preferred viewing position.

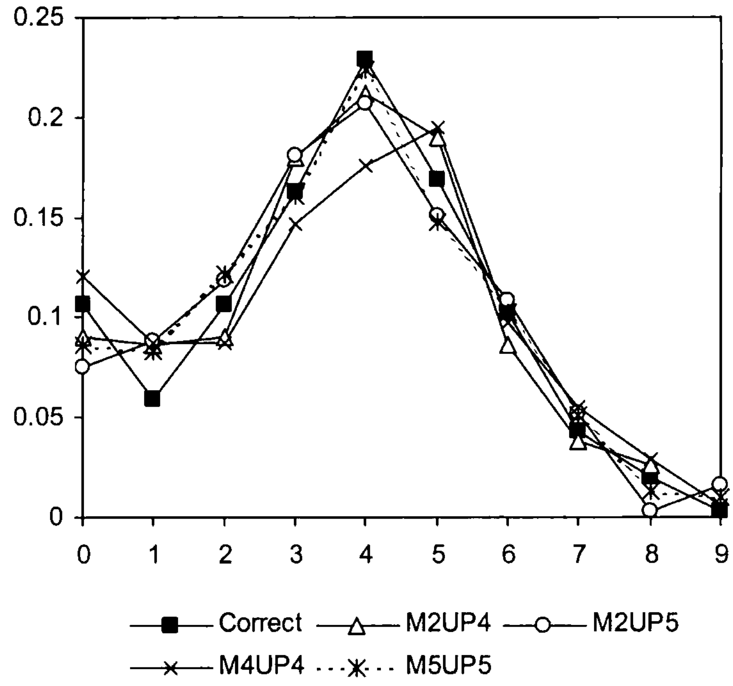

Figure 3.1 Experiment 2. First fixation landing position distributions on the critical string. Landing position zero is the space before the word and landing position one is the first letter of the word.

Incoming saccade extent and launch site. Table 3.3 shows the mean saccade extents and launch sites for each condition. There were no effects of spelling on the launch site (*F*'s < 1) or incoming saccade extent, F_1 (4, 156) = 1.43, p = .228, *MSE* = 0.7; $F_2 < 1$, prior to fixating the critical string.

Table 3.4 *Experiment 2. Probability of Skipping, Making a Single Fixation and Refixating (≥ Two) the Critical String on First Pass. Standard Deviations in Parentheses.*

Experiment 2		Critical string fixation probabilities		
		Skip	Single	≥Two
Correct		0.03 (0.12)	0.73 (0.2)	0.24 (0.17)
Second letter misspelled	Illegal at 4th (M2UP4)	0.01 (0.06)	0.62 (0.25)	0.37 (0.24)
	Illegal at 5th (M2UP5)	0.01 (0.05)	0.66 (0.22)	0.33 (0.22)
Letter at point of illegality misspelled	Illegal at 4th (M4UP4)	0.02 (0.06)	0.6 (0.25)	0.38 (0.27)
	Illegal at 5th (M5UP5)	0.02 (0.06)	0.65 (0.24)	0.33 (0.25)

Refixations. Table 3.4 shows the probability of refixating the critical string for all of the data. Table 3.5 shows the probability of refixating on the critical string for those cases in which the critical string was fixated on first pass. There was a significant effect of spelling on the probability of refixating the critical string on first pass, F_1 (4, 156) = 3.5, $p < .01$, $MSE = 317$; F_2 (4, 156) = 2.4, $p = .05$, $MSE = 371$. Simple effects showed that the correctly spelled condition was significantly less likely to be refixated on first pass than the M2UP4, F_1 (1, 39) = 10.46, $p < .01$, $MSE = 585$; F_2 (1, 39) = 7.69, $p < .01$, $MSE = 660$, and M4UP4, F_1 (1, 39) = 10.56, $p < .01$, $MSE = 680$; F_2 (1, 39) = 6.1, $p = .02$, $MSE = 895$ conditions. Although the correctly spelled condition was numerically more likely to be refixated than the M2UP5, F_1 (1, 39) = 3.38, $p = .07$, $MSE = 724$; F_2 (1, 39) = 2.46, $p = .125$, $MSE = 676$, and M5UP5, F_1 (1, 39) = 4.92, $p = .03$, $MSE = 668$; F_2 (1, 39) = 2.05, $p = .16$, $MSE = 1149$, conditions, these differences were not reliable. For the misspelled conditions, there were also no effects of misspelling position (F's < 1), point of illegality, F_1 (1, 39) = 3.76, $p = .06$, $MSE = 210$; F_2 (1, 39) = 2.37, $p = .132$, $MSE = 329$, and no interaction between these variables (F's < 1). Nevertheless, the tendency for misspelled words to be refixated more often than correctly spelled words is consistent with the longer reading times shown on the misspelled words. Again these results are consistent with Experiment 1, the high frequency misspelled critical strings are more likely to be refixated than the correctly spelled words.

Table 3.5 *Experiment 2. For Cases in Which the Critical String was Fixated on First Pass: Probability of Refixating the Critical String. Probability of First Refixating to the Left of the Initial Fixation on the Critical String. Length and Landing Position of Rightward Refixation Saccades, Standard Deviations in Parentheses.*

Experiment 2		Probability of refixating	Probability of leftward refixation	Rightward saccade length	Rightward landing position
Correct		0.25 (0.21)	0.23 (0.38)	4.8 (1.6)	6.1 (1.5)
Second letter misspelled	Illegal at 4th (M2UP4)	0.37 (0.25)	0.44 (0.35)	4.8 (1.8)	6.5 (1.5)
	Illegal at 5th (M2UP5)	0.33 (0.22)	0.29 (0.36)	4.4 (1.8)	6.4 (1.4)
Letter at point of illegality misspelled	Illegal at 4th (M4UP4)	0.39 (0.26)	0.34 (0.41)	4.4 (1.7)	6.1 (1.6)
	Illegal at 5th (M5UP5)	0.34 (0.25)	0.28 (0.35)	4.8 (2.0)	6.5 (1.5)

The probability of refixating to the left of the initial fixation position was numerically higher when the critical string was misspelled compared to when it was spelled correctly, the effect of spelling was significant across items[1], F_2 (4, 100) = 4.57, $p < .01$, $MSE = 796$, but not participants, F_1 (4, 96) = 1.95, $p = .109$, $MSE = 894$. Therefore similar to Experiment 1 there were no reliable effects of "high frequency" misspellings on the direction of refixations. Only 12 participants and 18 items produced rightward refixation saccades on the critical string in all of the conditions. Consequently, there was insufficient data to examine whether spelling influenced rightward refixation saccade lengths and fixation positions.

[1] In Experiment 2, for the analyses of the probability of refixating to the left, only participants and items that produced refixations in all of the conditions were included. Consequently the F_1 analysis was based on 25 participants and the F_2 analysis was based on 26 items.

3.1.3: Discussion

Experiment 2 clearly showed that when the word initial trigram is high in frequency, misspellings in the second, fourth or fifth position, do not influence saccade programming to that word. Furthermore, four or five letter word initial illegal letter sequences also have no effect on fixation positions. That is, there were no effects of spelling on saccade lengths into, launch sites before or landing positions on the critical string. The results do not support the suggestion that the detection of illegality can influence first fixation positions on words. That is, the results do not support the first suggested explanation proposed in Section 2.2.3 for the high frequency misspelling result in Experiment 1.

Similar to Experiment 1, the results provide no support for the notion that non-fixated text influences prior fixation durations. There were no effects of spelling on prior fixation durations or reading times on word n-1. In addition, there were no effects of spelling on the probability of refixating word n-1. In contrast to the high frequency misspelling condition in Experiment 1, there was also no evidence that orthographically regular misspellings can influence the probability of skipping the previous word. Therefore Experiment 2 provides no support for studies that suggest that lexical candidate generation processes can produce parafoveal-on-foveal effects (Kennedy, 1998, 2000b; Kennedy et al., 2002; Pynte et al., in press).

3.2: Experiment 3

The results of Experiment 2 suggest that the high frequency misspelling result in Experiment 1 was not due to the detection of illegal letter sequences. However, it is possible that the different landing positions on the correct and high frequency misspelled conditions in Experiment 1 may have been due to small differences in the number of possible word candidates that could be generated from the word initial letters (as suggested in Section 2.2.3). Experiment 3 examined this possibility by controlling for orthographic familiarity and manipulating the informativeness of the word initial letters. An informative letter sequence generates few possible word candidates consistent with these letters and an uninformative letter sequence generates many possible word candidates consistent with these letters. Materials were constructed in which a critical string was spelled correctly with an uninformative initial trigram, misspelled with an uninformative initial trigram, or misspelled with an informative initial trigram.

Each of the three explanations for the results of Experiment 1 described in Section 2.2.3 generates different predictions for Experiment 3. First, if fixation positions are influenced by any kind of illegality then landing positions should be nearer the beginning of the critical string in both of the misspelled conditions, compared to the correctly spelled condition. Note that the results of Experiment 2 suggest that this is not the case, the presence of misspellings alone did not influence saccade programming.

The second explanation suggests that if preprocessing of possible lexical candidates for non-fixated words influences where words are first fixated then the informativeness of word beginnings should influence landing positions. Previous studies of the effect of informativeness on fixation positions (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987) would predict that fixation positions should be nearer the beginning of the informative misspelled strings compared to the uninformative misspelled and correctly spelled strings. In contrast, the ideal observer model of reading (Legge et al., 1997) might predict that fixations should land further into words with informative beginning letter sequences because the word candidates that might be generated from the initial letter sequences are likely to have been exhaustively processed in non-foveal vision. Therefore, regardless of the direction of the effects, if fixation positions are different for the informative and uninformative misspelled strings then the results will indicate that preprocessing of possible lexical candidates can influence saccade computation.

The third possibility, is that if processing beyond the level of the orthographic familiarity of word initial trigrams does not influence where words are first fixated then there should be no difference in landing positions for letter strings with equally familiar initial letter sequences. That is to say, there should be no differences in fixation positions between the correct, informative misspelled or uninformative misspelled conditions because there is no difference in initial letter sequence familiarity between these conditions. This third possibility is consistent with models of eye movements in reading (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990) and with evidence suggesting that the lexical characteristics of text can not be preprocessed (Lima & Inhoff, 1985) or influence where words are first fixated (Beauvillain et al., 1996; Hyönä, 1995; Rayner & Morris, 1992; Underwood et al., 1989).

Previous studies of the effects of orthography on landing positions (Beauvillain & Doré, 1998; Doré & Beauvillain, 1997; Hyönä, 1995; Radach et al., 2003; Vonk et al., 2000) have confounded the variables of orthographic familiarity and informativeness. Kennedy (2000b) did carefully manipulate these, and other, variables in artificial task experiments but found no effects of letter sequence frequency on landing positions. Experiment 3 provides a test of the hypothesis that informativeness of the word initial trigam, independent of the orthographic familiarity of the word initial trigram, influences fixation positions.

Furthermore, as explained in Section 1.5 and at the beginning of this Chapter, it has been argued that preprocessing of possible lexical candidates can influence fixations on previous words (Kennedy, 1998, 2000b; Kennedy et al, 2002; Pynte et al., in press). Experiment 2 may not have provided a strong test of this suggestion because similar numbers of candidates could be generated from the word initial letters in each of the conditions. In contrast, in Experiment 3 the number of candidates that might be generated on the basis of the word initial trigram is experimentally manipulated. Therefore Experiment 3 provides a very strong test of the hypothesis that lexical candidate generation processing of non-foveal words can influence the duration of previous fixations and prior fixation probabilities.

3.2.1: Method

Participants. Twenty-four native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected to normal vision and were naïve in relation to the purpose of the experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Materials and Design. Word frequencies and n-gram frequencies were calculated using the CELEX English word form corpus (Baayen, et al, 1995). All of the critical strings were eight or nine characters long ($M = 8.5$, $SD = 0.5$) and the mean word frequency in counts per million was 17 ($SD = 29.5$). There were three conditions that were manipulated within participants and items. The critical strings were spelled correctly (e.g. *escalator*) or the second letter was misspelled to create either an uninformative (e.g. *encalator*) or informative (e.g. *eacalator*) initial trigram.

Position specific n-gram frequencies were calculated in counts per 17.9 million. The mean initial trigram token frequencies were numerically higher in the uninformative (M = 8696, SD = 10545) and informative (M = 6879, SD = 10974) misspelled conditions compared to the correctly spelled condition (M = 4325, SD = 5262) although these differences were not significant (t's < -1.8, ps > .9). The uninformative misspelled condition also tended to have higher type frequency initial trigrams (M = 47, SD = 26) compared to the correctly spelled condition (M = 32, SD = 29) although this was not significant, t (23) = -1.72, p = .1. Importantly, the informative misspelled condition had significantly lower type frequency initial trigrams (M = 6, SD = 3) than both the correctly spelled condition, t (23) = 4.45, p < .01 and the uninformative misspelled condition, t (23) = 7.51, p < .01. The type and token frequencies of the initial bigrams followed a similar pattern. The type and token monogram frequencies of the misspelled second letter were significantly higher in the misspelled condition compared to the correctly spelled condition (t's > 2). Importantly, the initial trigrams of the misspelled conditions were not more orthographically unfamiliar than the correctly spelled condition.

The 24 critical strings were embedded in identical sentence frames for each condition. Each of the sentences was no longer than one line of text (78 characters) and the critical string appeared approximately in the middle of the sentence. The words before and after the critical string were either five or six letters long and had medium to high frequencies. Most of the sentences included context relevant to the critical string at the beginning of the sentence. See Appendix C for example experimental sentences and critical strings.

Three lists of 96 items were constructed and eight participants were randomly allocated to each list. Each list included 24 experimental items of which 8 items were from each of the three misspelling conditions. The conditions were rotated following a Latin square design. There were 16 misspelled filler items with misspellings in a variety of word lengths and in a variety of positions within the word and the sentence. There were also 56 filler items that were spelled correctly. Therefore of the 96 items, 32 contained a misspelling. Thirty-two of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences. The sentences were presented in a fixed random order with six filler sentences at the beginning.

Procedure. The experimental procedure was the same as in Experiment 1. The entire experiment lasted approximately 30 minutes and participants were given one break.

Analyses. The analyses were the same as in Experiment 1. 1.4 percent of trials were excluded due to either no first pass fixations on the sentence prior to word n-1 or tracker loss or blinks on first pass reading of word n-1 or the critical string.

3.2.2: Results

The results were analysed in the same manner as for Experiment 1. The mean error rate on the comprehension questions was two percent.

Table 3.6 *Experiment 3. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Standard Deviations in Parentheses.*

Experiment 3	Word n-1		Fixation n-1		
	FF	GD	All	n-1	≤3
Correct	271 (94)	305 (128)	260 (93)	260 (92)	252 (72)
Uninformative misspelling	261 (93)	292 (126)	256 (68)	261 (67)	257 (71)
Informative misspelling	263 (74)	294 (122)	264 (89)	259 (74)	259 (85)

Parafoveal-on-foveal effects. Table 3.6 shows the mean fixation durations prior to fixating the critical string. There were no significant effects of spelling on first fixation or gaze duration for word n-1 (F's < 1.1). The probability of refixating word n-1 on first pass was 0.12 when the critical string was spelled correctly and 0.1 when the critical string was misspelled with an informative or uninformative initial trigram, these differences were not significant (F's < 1). The probability of skipping word n-1 on first pass was 0.18 when the critical string was spelled correctly, 0.14 when the critical string was misspelled with an uninformative initial trigram and 0.15 when the critical string was misspelled with an informative initial trigram, these differences were not significant (F's < 1). There were no significant effects of spelling on the duration of the fixation prior to first fixating the critical string for all of the data, for saccades launched from word n-1 and for saccades launched from three or less characters from the critical string (F's < 1). Similar to Experiment 2, the results show no evidence of lexically based parafoveal-on-foveal effects on either fixation durations or fixation probabilities.

Table 3.7 *Experiment 3. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String and Word n+1. Fixation Duration After Leaving the Critical String (Fixation n+1). Standard Deviations in Parentheses.*

Experiment 3	Critical String			Fixation	Word n+1		
	FF	GD	TT	n+1	FF	GD	TT
Correct	302 (100)	360 (146)	446 (237)	277 (89)	286 (87)	306 (106)	353 (164)
Uninformative misspelling	340 (176)	518 (346)	793 (547)	280 (103)	292 (113)	321 (152)	405 (208)
Informative misspelling	358 (176)	525 (299)	779 (483)	291 (114)	298 (119)	333 (161)	429 (247)

Reading time measures. Table 3.7 shows the mean reading time measures on the critical string. There were significant effects of spelling on first fixation, F_1 (2, 46) = 8.75, p < .01, MSE = 19235; F_2 (2, 46) = 6.59, p < .01, MSE = 19378, gaze duration, F_1 (2, 46) = 19.56, p < .01, MSE = 207245; F_2 (2, 46) = 18.96, p < .01, MSE = 205442, and total time, F_1 (2, 46) = 56.22, p < .01, MSE = 16448; F_2 (2, 46) = 26.20, p < .01, MSE = 35531, on the critical string. For all measures reading times were longer on the two misspelled conditions compared to the correctly spelled condition (F's > 6.5, ps < .05). There were no significant differences in reading time between the uninformative and informative misspelling conditions (t's < 1.6, ps > .1).

Table 3.7 shows the mean reading times after leaving the critical string. There was no effect of spelling on the duration of the fixation after leaving the critical string or on first fixation durations on word n+1 (F's < 1.2). There were also no effects of spelling on gaze duration on word n+1, F_1 (2, 46) = 2.31, p = .11, MSE = 7719; F_2 < 1, or across items for total time (F_2 < 1) although there was a significant effect of spelling across participants for total time on word n+1, F_1 (2, 46) = 3.8, $p < .05$, *MSE* = 28584.

Therefore similar to Experiments 1 and 2, and in support of previous studies (Inhoff & Topolski, 1994; Rayner, Pollatsek et al., 1998; Underwood et al., 1988; Zola, 1984), reading times were longer on the misspelled words than the correctly spelled words. However in contrast to Experiments 1 and 2 there were no reliable spillover effects. The results indicate that misspelled words are more difficult to process than correctly spelled words. Furthermore, there were no differences in reading times on words that were misspelled with an informative or uninformative initial trigram. These results suggest that the time to process a misspelled word is not influenced by the number of possible candidates that are generated by the initial trigram.

Table 3.8 *Experiment 3. Mean Landing Positions, Incoming Saccade Extents and Launch Sites. Standard Deviations in Parentheses.*

Experiment 3	Landing position	Saccade extent	Launch site
Correct	3.5 (2.1)	8.4 (2.3)	4.9 (2.7)
Uninformative misspelling	3.5 (2.1)	8.4 (2.5)	4.9 (2.9)
Informative misspelling	3.6 (2.2)	8.3 (2.8)	4.8 (2.8)

Landing position. Table 3.8 shows the mean first fixation positions on the critical string in each of the conditions. There were no significant effects of spelling on landing position (*F*s < 1). Figure 3.2 shows the distribution of landing positions for each of the conditions, note that most fixations landed on the preferred viewing position.

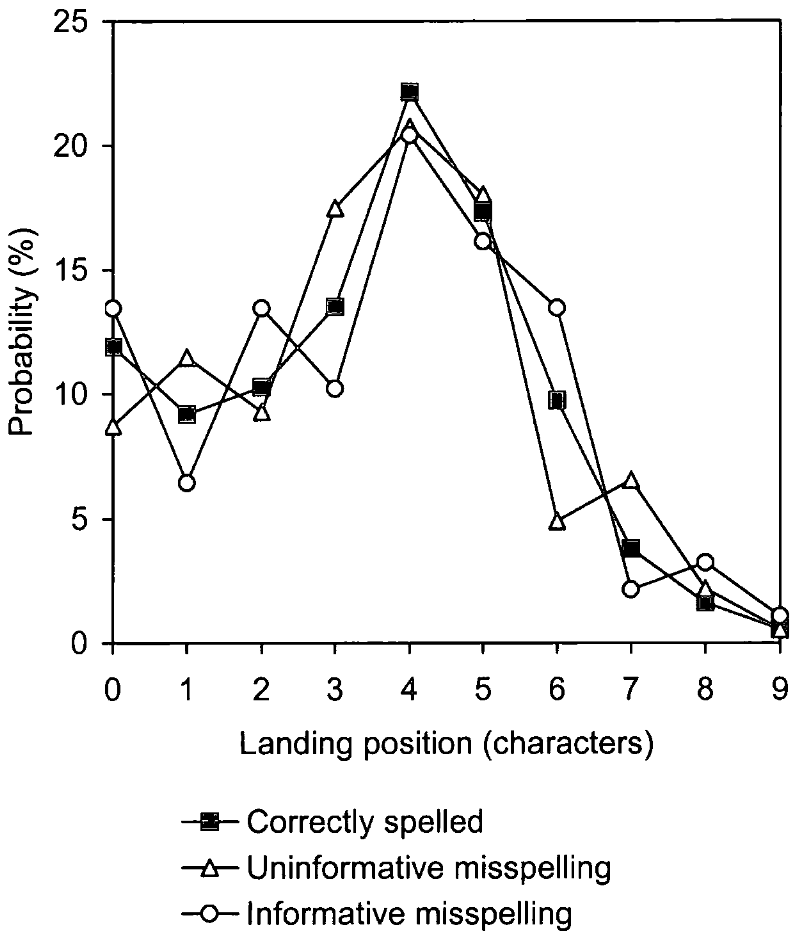

Figure 3.2 Experiment 3. First fixation landing position distributions on the critical string. Landing position zero is the space before the word and landing position one is the first letter of the word.

Incoming saccade extent and launch site. Table 3.8 shows the mean saccade extents and launch sites for each condition. There were no effects of spelling on the launch site or incoming saccade extent prior to fixating the critical string (F's < 1).

Table 3.9 *Experiment 3. Probability of Skipping, Making a Single Fixation and Refixating (≥ Two) the Critical String on First Pass. Standard Deviations in Parentheses.*

Experiment 3	Critical String fixation probabilities		
	Skip	Single	≥Two
Correct	0.03 (0.09)	0.74 (0.16)	0.23 (0.15)
Uninformative misspelling	0.02 (0.05)	0.6 (0.2)	0.38 (0.2)
Informative misspelling	0.01 (0.04)	0.59 (0.18)	0.4 (0.18)

Refixations. Table 3.9 shows the probability of skipping or making one or more than one fixation on the critical string on first pass. Table 3.10 shows the probability of refixating the critical string for those cases in which the critical string was fixated on first pass. There was a significant effect of spelling on the probability of refixating the critical string on first pass, F_1 (2, 46) = 9.57, $p < .01$, $MSE = 214$; F_2 (2, 46) = 6.61, $p < .01$, $MSE = 306$. The correctly spelled condition was significantly less likely to be refixated on first pass than the uninformative misspelling condition, F_1 (1, 23) = 9.74, $p < .01$, $MSE = 511$; F_2 (1, 23) = 11.89, $p < .01$, $MSE = 443$, or the informative misspelling condition, F_1 (1, 23) = 16.08, $p < .01$, $MSE = 441$; F_2 (1, 23) = 10.22, $p < .01$, $MSE = 664$. There were no differences in the probability of refixating the informative compared to the uninformative misspelled critical strings on first pass (t's < 1). Similar to the reading time measures, these results suggest that the misspelled words were more difficult to process because they produced more first pass refixations.

Table 3.10 *Experiment 3. For Cases in Which the Critical String was Fixated on First Pass: Probability of Refixating the Critical String. Probability of First Refixating to the Left of the Initial Fixation on the Critical String for Multiple First Pass Fixation Cases. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 3	Refixation probability	Leftward refixation probability	Rightward saccade length	Rightward landing position
Correct	0.23 (0.15)	0.16 (0.22)	4.7 (1.7)	5.9 (1.5)
Uninformative misspelling	0.38 (0.2)	0.29 (0.29)	4.5 (1.9)	6.3 (1.6)
Informative misspelling	0.4 (0.18)	0.39 (0.3)	4.7 (1.9)	6.1 (1.4)

Table 3.10 also shows the probability of initially refixating to the left of the initial fixation position on the critical string. There was a significant effect of spelling on the probability of first refixating to the left of the initial fixation position[2], F_1 (2, 38) = 3.33, $p < .05$, $MSE = 2835$; F_2 (2, 36) = 4.95, $p < .05$, $MSE = 3202$. Refixations to the left of the initial fixation position were significantly more likely in the informative misspelled condition compared to the correctly spelled condition, F_1 (1, 19) = 8.71, $p < .05$, $MSE = 10945$; F_2 (1, 18) = 7.85, $p < .05$, $MSE = 11299$. Leftward refixations were numerically more likely in the uninformative misspelled condition compared to the correctly spelled condition but this effect was significant across items, F_2 (1, 18) = 9.1, $p < .05$, $MSE = 7533$, but not participants, F_1 (1, 19) = 2.53, $p = .129$, $MSE = 4835$. There was no difference in the probability of refixating to the left between the uninformative and informative conditions (t's <1.2). The results show that misspellings increase the probability of making regressive refixations. A similar, but unreliable, trend was shown in Experiment 2. Eighteen participants and 18 items produced rightward refixation saccades in all three of the conditions. Analyses based on these data showed that spelling had no effect on either rightward refixation saccade length or landing position (F's < 1).

[2] In Experiment 3, for the analyses of the probability of refixating to the left, only participants and items that produced refixations in all of the conditions were included. Consequently the F_1 analysis was based on 20 participants and the F_2 analysis was based on 19 items.

3.2.3: Discussion

The introduction to Section 3.2 proposed three possible outcomes for the results of Experiment 3. First, if the presence of any illegality influenced fixation positions then landing positions should have been different in the two misspelled conditions compared to the correctly spelled condition, however landing positions were the same in all three of the conditions. Therefore, similar to Experiment 2, the results suggest that the presence of any non-foveal illegality does not influence saccade programming. The second suggestion was that if preprocessing of possible lexical candidates influenced saccade programming then landing positions should have been different in the informative misspelled condition compared to the uninformative misspelled and correctly spelled condition. However, again no such effects were found. Therefore the results suggest that preprocessing of possible lexical candidates (informativeness) does not influence saccade programming. However the results are consistent with the third suggestion which was that processing beyond the level of the orthographic familiarity of words does not influence where words are first fixated. Importantly, these results imply that the effects of misspellings shown in Experiment 1 are due to orthographic, rather than lexical, preprocessing.

The results support evidence that shows that lexical characteristics of words can not be preprocessed if they are subsequently fixated (Lima & Inhoff, 1985), that informativeness of non-foveal words does not influence where they are subsequently fixated (Beauvillain et al., 1996; Hyönä, 1995; Rayner & Morris, 1992; Underwood et al., 1989), and with current models of eye movements in reading (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990). However the results are inconsistent with the finding in Experiment 1 that fixation positions land nearer to the beginning of words misspelled with a high frequency initial trigram compared to the correctly spelled words. Furthermore, the results are also inconsistent with previous studies suggesting that the distribution of informativeness within words can influence where words are first fixated (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987).

Contrary to Experiment 1, and in line with numerical differences in Experiment 2, the high frequency misspellings in this experiment did produce more refixations to the left of the initial fixation position compared to the correctly spelled condition. Nevertheless, similar to the effects of the orthographically irregular misspellings on refixations in Experiment 1, it is difficult to interpret this result. That is, misspellings might have induced problem solving processes whilst fixating the misspelled words, which may have influenced eye movement behaviour differently to normal reading.

The results also provide no support for the notion that non-fixated text influences fixation durations. Similar to Experiments 1 and 2, there were no effects of spelling on the probability of refixating word n-1, or on fixation durations prior to fixating the critical string. Similar to Experiment 2 and opposite to Experiment 1, there were also no effects of spelling on the probability of skipping word n-1. Similar to previous studies of parafoveal-on-foveal effects (Kennedy, 1998, 2000b; Kennedy et al., 2002; Pynte et al, in press), Experiment 3 directly manipulated the number of word candidates that might be generated from the word initial letters. However in contrast to these studies Experiment 3 showed no evidence of parafoveal-on-foveal effects on either prior fixation durations or prior fixation probabilities.

3.3: Conclusions

There is a clear inconsistency between the landing position and skipping results for the high frequency misspelling condition in Experiment 1 and the absence of any effect of misspellings in Experiments 2 and 3. It is possible that the high frequency misspelling result in Experiment 1 was caused by other factors. For example, the presence of orthographically irregular misspellings might have somehow increased the salience of illegal letter sequences within words. Nevertheless, the experiments presented in this chapter provide clear evidence that words misspelled with high frequency initial letter sequences do not ordinarily influence where words are first fixated. It must be concluded that influences on landing positions beyond the level of the orthographic familiarity of the initial trigrams are at best unreliable and possibly spurious.

The results of both Experiments 2 and 3 are consistent with evidence that shows that lexical characteristics of words can not be preprocessed if they are subsequently fixated. That is, as explained in Section 1.1.3, orthographic and phonological information can be preprocessed and integrated across saccades to facilitate preview benefit. However possible lexical candidates for non-foveal words can not be preprocessed and integrated across saccades to facilitate future foveal processing of that word. For example, Lima and Inhoff (1985) showed that the amount of preview benefit was the same for words with initial letters that generated few or many possible word candidates. In line with these results, Experiments 2 and 3 show that the number of potential word candidates that can be generated from the word initial letters can not be preprocessed such that it influences saccade programming. However it should be noted that such lexical information can be preprocessed from non-foveal words if it is used to influence the probability of skipping a word (see Section 1.2.3).

Importantly, Experiments 2 and 3 specifically manipulated the lexical characteristics of words but these had no influence on fixation durations or probabilities prior to fixating the critical string. Therefore, along with Experiment 1, the experiments in this Chapter provide further evidence against the existence of robust parafoveal-on-foveal effects. The absence of parafoveal-on-foveal effects supports serial attention shift accounts of eye movements in reading (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press) and is inconsistent with parallel attention allocation explanations (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980).

Chapter 4

Orthographic Influences on Fixation Positions

Experiment 1 showed that initial fixation positions land nearer to the beginning of words misspelled to create orthographically irregular initial letter sequences compared to words that are spelled correctly. However, all misspellings produce illegal letter strings which might influence saccade programming by preprocessing of the lexical characteristics of those words. Experiments 2 and 3 suggest that lexical characteristics of non-foveal text do not influence where words are first fixated. These results indicate that the effect of misspellings on initial fixation positions in Experiment 1 must have been due to sub-lexical orthographic processing rather than lexical candidate generation processes. However misspellings provide a very strong test of the hypothesis that word characteristics influence fixation positions. It is possible that misspellings might be sufficiently unusual that they are able to influence saccade programming in a way that correctly spelled English words cannot. There is also the possibility that because readers were aware of the misspellings they may have adopted strategies that are not ordinarily used in reading of correctly spelled text. Consequently, Experiments 4 and 5 were designed to investigate whether the frequency of word initial letter sequences influences landing positions in the reading of correctly spelled English sentences.

Experiment 4 (Section 4.1) investigates whether orthographic regularity influences fixation positions. Experiment 5 (Section 4.2) investigates whether orthographic regularity influences fixation positions in upper, as well as lower, case text. Experiment 5 also provided an opportunity to examine the effects of case on general eye movement behaviour (Section 4.3). Together, Experiments 4 and 5 provided a large data set which enabled a number of further analyses of oculomotor behaviour to be undertaken (Section 4.4).

4.1: Experiment 4

A number of studies have suggested that orthography can influence where words are fixated. However these studies have used artificial tasks (Beauvillain &

Doré, 1998; Beauvillain et al., 1996; Doré & Beauvillain, 1997), languages other than English (Hyönä, 1995; Radach et al., 2003; Vonk et al., 2000) or misspelled words (Experiment 1, Chapter 2). In addition, as explained in Section 1.3.1, a number of studies using artificial tasks (Kennedy, 1998, 2000b; Radach et al., 1995), corpus studies (Radach & Kempe, 1993; Radach & McConkie, 1998), and sentence reading experiments (Liversedge & Underwood, 1998), have shown no influence of orthography on word initial fixation positions. It is unclear whether the inconsistency between the findings of these studies might be due to the use of insufficiently strong manipulations of orthography, differences between languages, or that the effect of orthography on fixation positions is simply not robust. Consequently Experiment 4 aimed to determine whether orthography influences initial fixation positions on correctly spelled words in English sentences, using the strongest possible manipulations of orthographic regularity. For simplicity, Experiment 4 has just two conditions comparing fixations on critical words with orthographically regular and orthographically irregular beginning letter sequences.

Probably the most widely cited study of the effects of orthography on fixation positions (Hyönä, 1995) used very infrequent individual letters to create unfamiliar letter sequences and it is unclear whether other studies of fixation positions in sentences (Radach et al., 2003; Vonk et al., 2000) controlled for this variable. Importantly, in Experiment 4 individual letter frequency of the initial three letters of the critical words was very carefully controlled. Therefore any effects of the orthographically regular and irregular beginning words on initial fixation positions must be due to non-foveal preprocessing of letter sequences rather than individual letters.

In addition, Experiment 4 provides yet another opportunity to test for parallel processing of words in the form of parafoveal-on-foveal effects (see Section 1.5). In order to produce the strongest possible manipulation of orthographic familiarity, the orthographically irregular words had word initial letter sequences that were not only less familiar than those of the orthographically irregular words, but which also generated fewer possible word candidates. Therefore if non-foveal preprocessing of either orthographic or lexical information is processed in parallel on the previous fixation (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980) then Experiment 4 should show parafoveal-on-foveal effects. As in the other Experiments, two types of parafoveal-on-foveal effects were investigated. That is, whether the characteristics of the critical string influence fixation durations or fixation probabilities before the critical word is fixated.

4.1.1: Method

Participants. Forty-four native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected to normal vision and were naïve in relation to the purpose of the experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Materials and Design. Word frequencies and n-gram frequencies were calculated using the CELEX English word form corpus (Baayen et al., 1995). The critical words had orthographically regular (e.g. *miniature*) or irregular (e.g. *ergonomic*) word beginnings and these two conditions were manipulated within participants and items. As a result of this manipulation, critical words in the regular condition also had a significantly higher word frequency in counts per million (M = 24, SD = 29) than the critical words in the irregular condition (M = 1, SD = 2), t (23) = 3.8, $p < .01$.

Position specific n-gram frequencies were calculated in counts per 17.9 million. Type frequency is the total number of words that contain a particular letter sequence. Token frequency is the sum of the frequencies of the words that contain a particular letter sequence. The initial trigram type and token frequencies were significantly higher for the orthographically regular condition (type: M = 176, SD = 103; token: M = 42588; SD = 66006) compared to the orthographically irregular condition (type: M = 7 SD = 4; token: M = 171, SD = 160), t's > 3.1, ps < .01. The initial bigram type and token frequencies were also significantly higher for the orthographically regular condition (type: M = 735, SD = 371; token: M = 155116, SD = 132526) compared to the orthographically irregular condition (type: M = 90, SD = 72; token: M = 15347; SD = 17440), t's > 5, ps < .01. The second bigram (second and third letter) type and token frequencies were also higher for the orthographically regular condition (type: M = 1721, SD = 1758; token: M = 527968, SD = 804679) compared to the orthographically irregular condition (type: M = 781, SD = 1218; token: M = 240211; SD = 364530), the difference was significant for type, t = 2.8, p < .01, but not token, t = 1.7, p = .11, frequency. There were no significant differences in non-position specific type or token monogram frequency between the two conditions for the first, second or third letters of the critical words (t's < 1.2).

There were 24 critical words in each condition, all were either nine or ten letters long and they were matched for length across the two conditions with a mean word length of 9.4 characters (SD = 0.5). Each pair of critical words was embedded roughly in the middle of the same sentential frame up to and including the word after the critical word. Each of the sentences was no longer than one line of text (78 characters). The words before and after the critical words were either five or six letters long and had medium to high frequencies. The critical words were not predictable from the prior sentential context. Twelve participants were given sentence fragments up to the position of the critical word and they were asked to write down what they thought the next word might be. None of the participants guessed any of the critical words. See Appendix D for examples of experimental sentences and critical words.

Two lists of 72 sentences were constructed and 22 participants were randomly allocated to each list. Each list included all 48 experimental sentences and 24 filler sentences. Within each list the sentences were presented in a fixed random order with four filler sentences at the beginning. For each condition, 12 experimental sentences were presented in the first half of one list and the second half of the other list. Twenty-four of the sentences were followed by a comprehension question.

Procedure. The procedure was the same as for Experiment 1. Participants were instructed to understand the sentences to the best of their ability. The entire experiment lasted approximately 30 minutes and participants were given one break.

Analyses. The analyses were the same as for Experiment 1. 4.4 percent of trials were excluded due to either no first pass fixations on the first region or tracker loss or blinks on first pass reading of word n-1 or the critical word.

4.1.2: Results

The results were analysed using the same eye movement measures as used in Experiment 1. Paired samples t-tests were undertaken with participants (t_1) and items (t_2) as random variables. The mean error rate on the comprehension questions was nine percent, indicating that participants properly read and understood most of the sentences.

Table 4.1 *Experiment 4. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical Word (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical Word (≤3). Standard Deviations in Parentheses.*

Experiment 4	Word n-1		Fixation n-1		
	FF	GD	All	n-1	≤3
Orthographically regular	264 (79)	299 (112)	257 (80)	261 (79)	254 (77)
Orthographically irregular	265 (82)	297 (110)	259 (88)	262 (82)	256 (79)

Parafoveal-on-foveal effects. Table 4.1 shows the mean reading time measures on word n-1 and mean fixation durations prior to fixating the critical word. There were no significant effects of regularity on first fixation durations on word n-1, gaze durations on word n-1, the duration of the fixation prior to first fixating the critical word for all of the data, for saccades launched from word n-1 and for saccades launched from three or less characters from the critical word (t's < 1). Therefore the word initial letter sequences of the critical word did not influence fixation durations until the critical words were directly fixated. That is, there was no evidence to suggest that non-foveal preprocessing of words can influence prior fixation durations (parafoveal-on-foveal effects).

Table 4.2 *Experiment 4. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical Word and Word n+1. Fixation Duration After Leaving the Critical Word (Fixation n+1). Standard Deviations in Parentheses.*

Experiment 4	Critical Word			Fixation	Word n+1		
	FF	GD	TT	n+1	FF	GD	TT
Orthographically regular	300 (98)	393 (162)	503 (270)	277 (94)	282 (92)	298 (105)	357 (169)
Orthographically irregular	339 (131)	521 (272)	640 (352)	273 (97)	276 (94)	295 (110)	340 (161)

Reading time measures. Table 4.2 shows the mean reading time measures on the critical word. First fixations, t_1 (43) = 8.71, $p < .01$; t_2 (23) = 5.58, $p < .01$, gaze durations, t_1 (43) = 8.08, $p < .01$; t_2 (23) = 9.25, $p < .01$, and total time, t_1 (43) = 7.18, $p < .01$; t_2 (23) = 6.72, $p < .01$, were significantly longer on irregular than regular beginning words. These results correspond to Lima and Inhoff's (1985) finding that fixations are longer on words with constraining (infrequent) than less constraining (frequent) initial trigrams (see also Radach et al., in press; Vonk et al., 2000). The results might also reflect the standard word frequency effect, fixations are longer on infrequent (orthographically irregular beginning) than frequent (orthographically regular beginning) words (e.g. Inhoff & Rayner, 1986).

Table 4.2 shows the mean reading time measures for fixations after the critical word. There was no effect of orthography on the duration of the fixation after leaving the critical word (t's < 1.1), the first fixation on word n+1, t_1 (43) = 1.85, $p = .072$; $t_2 <$ 1.1, gaze duration on word n+1, t_1 (43) = 1.32, $p = .195$; $t_2 < 1$, and no reliable effects of orthography on the total time on word n+1, t_1 (43) = 2.65, $p = .01$; t_2 (23) = 1.7, $p =$ .102. Therefore there is no evidence for continued processing of the orthographically irregular compared to orthographically regular words after leaving the critical word.

Table 4.3 *Experiment 4. Mean Landing Positions, Incoming Saccade Extents and Launch Sites. Standard Deviations in Parentheses.*

Experiment 4	Orthography	Landing position	Saccade extent	Launch site
All data	Regular	3.7 (2.1)	8.3 (2.6)	4.6 (3)
	Irregular	3.6 (2)	8.2 (2.8)	4.7 (2.9)
	Difference	0.1	0.1	-0.1
Launch word n-1	Regular	4 (1.9)	7.6 (1.7)	3.6 (1.7)
	Irregular	3.8 (1.8)	7.5 (1.7)	3.7 (1.6)
	Difference	0.2	0.1	-0.1
Launch ≤3 characters	Regular	4.9 (1.5)	7.1 (1.5)	2.1 (0.8)
	Irregular	4.6 (1.5)	6.9 (1.5)	2.2 (0.8)
	Difference	0.3	0.2	-0.1

Landing positions. Table 4.3 shows the mean first fixation positions on the critical word. The mean first fixation position on the critical word was 0.1 characters nearer the word beginning for irregular than regular beginning words, but this difference was not significant, $t_1(43) = 1.44, p = .158$; $t_2\ (23) = 1.25, p = .223$. Figure 4.1 shows the distribution of landing positions for each condition. The preferred viewing position curve for the orthographically irregular beginning words is shifted to the left compared to that for the regular beginning words.

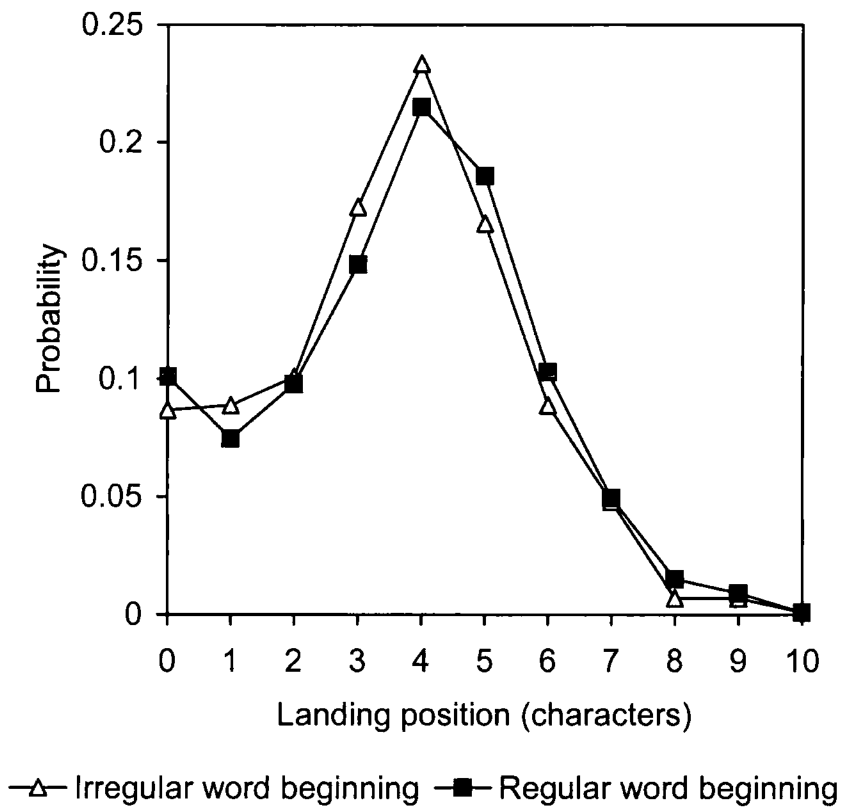

Figure 4.1 Experiment 4. First fixation landing position distributions on the critical word. Landing position zero is the space before the word and landing position one is the first letter of the word.

Since text that is further from fixation is visually degraded relative to that nearer to fixation, studies frequently analyse non-foveal text processing as a function of launch site (e.g. Kennison & Clifton, 1995; Lavigne et al., 2000; Rayner, 1975; Rayner et al., 2001). Saccades launched from further away might be less likely to be influenced by the characteristics of the critical word. When the analyses were restricted to the 84 percent of saccades launched from word n-1, the mean first fixation position was 0.2 characters significantly nearer the word beginning for irregular than regular beginning words, $t_1(43) = 2.12, p = .04$; $t_2\ (23) = 2.3, p = .03$. When the analyses were restricted to the 41 percent of saccades launched from three or less characters before the critical word, the mean first fixation position was 0.3 characters significantly nearer the word beginning for irregular than regular beginning words, $t_1(43) = 2.52, p = .02$; $t_2\ (23) = 2.91, p = .01$. For saccades launched from word n-1 and cases in which a single fixation was made on the critical word, initial fixation positions were also significantly nearer the beginning of the critical word if it was orthographically irregular ($M = 4.0$, $SD = 1.5$) compared to if it was orthographically regular ($M = 4.4$, $SD = 1.5$), $t_1(43) = 3.03, p < .01$; $t_2\ (23) = 3.71, p < .01$. For cases in which a single fixation was made on word n-1 directly before fixating the critical word, initial fixation positions were also numerically nearer the beginning of the critical word if it was orthographically irregular ($M = 3.7$, $SD = 1.8$) compared to if it was orthographically regular ($M = 3.9$, $SD = 1.9$) and this was significant across items, $t_2\ (23) = 2.25, p = .03$, but not participants, $t_1(43) = 1.57, p = .123$. Therefore a range of different analyses all indicate that first fixations landed nearer to the beginning of orthographically irregular, compared to regular, beginning words.

As detailed in the Method (Section 4.1.1), on average the orthographically regular words had higher word frequency than the orthographically irregular words. Therefore it is possible that the landing position effects might be explained by preprocessing of word frequency rather than the frequency of initial letter sequences of the non-foveal word. In order to investigate this possibility the items were divided into two equal groups, one in which the orthographically regular words had low frequency (10 or less counts per million) and one in which the orthographically regular words had high frequency (more than 10 counts per million). The variable of orthographically regular word frequency was then entered as a variable into the ANOVA of landing positions on the critical word for saccades launched from the previous word. If the effects of orthographic regularity on landing position were driven by word frequency then there should be no difference in landing position for orthographically regular and irregular words when both are low frequency (10 or less counts per million). That is, there would be an interaction between orthographic regularity and the frequency of the orthographically regular words. In fact, there were significant effects of regularity, $F_1(1, 43) = 7.48, p < .01, MSE = 0.53$; $F_2\ (1, 22) = 10.9, p < .01, MSE = 0.079$, but critically no significant effects of orthographically regular word frequency, $F_1(1, 43) = 2.29, p = .137, MSE = 0.43$; $F_2 < 1$, and no interaction (F's < 1). The absence of any effects of word frequency on landing positions is consistent with the results of Rayner et al. (1996). Furthermore, the effects of orthographic regularity on first fixation landing positions were independent of word frequency. The results therefore provide clear evidence that non-foveal orthographic processing influences where words are first fixated for saccades launched from near launch sites.

Table 4.4 *Experiment 4. Probability of Skipping and Refixating Word n-1 Directly Before Fixating the Critical Word. Probability of Skipping, Making a Single Fixation and Refixating (≥Two) the Critical Word on First Pass. Standard Deviations in Parentheses.*

Experiment 4	Word n-1 skip	Word n-1 refixation	Critical word fixation probabilities		
			Skip	Single	≥Two
Orthographically regular	0.16 (0.17)	0.13 (0.12)	0.02 (0.05)	0.64 (0.15)	0.34 (0.16)
Orthographically irregular	0.16 (0.17)	0.13 (0.14)	0.01 (0.02)	0.51 (0.21)	0.48 (0.22)

Incoming saccade extent and launch site. Table 4.3 also shows the mean saccade lengths and launch sites corresponding to the analyses of landing positions above. For all of the data and for saccades launched from the previous word there were no effects of launch site (t's < 1.2) or saccade length into the critical word (t's < 1.5). For saccades launched from three characters from the beginning of the critical word launch sites were numerically further away and saccade lengths were numerically shorter for the orthographically irregular, compared to regular beginning words, but there were no reliable effects of launch site, $t_1(43) = 1.72, p = .09$; $t_2\,(23) = 2.04, p = .05$, and no effects of saccade length, $t_1(43) = 1.07, p = .29$; $t_2\,(23) = 1.77, p = .09$. Table 4.4 shows that there were no effects of orthography on the probability of refixating or skipping word n-1 directly before fixating the critical word (t's < 1). Although there were no significant effects of saccade length, Figure 4.2 shows that the mean landing positions on the critical word were numerically nearer the beginning of the word for the orthographically irregular compared to the orthographically regular beginning condition for most of the launch sites near to the critical word. As explained in Section 1.3.1, differences in landing positions must be explained by either or both differences in saccade length or launch site. Although there were no significant effects of saccade lengths or launch sites in Experiment 4, the numerical differences shown in

Table 4.3 suggest that both these factors must have contributed to the landing position effect.

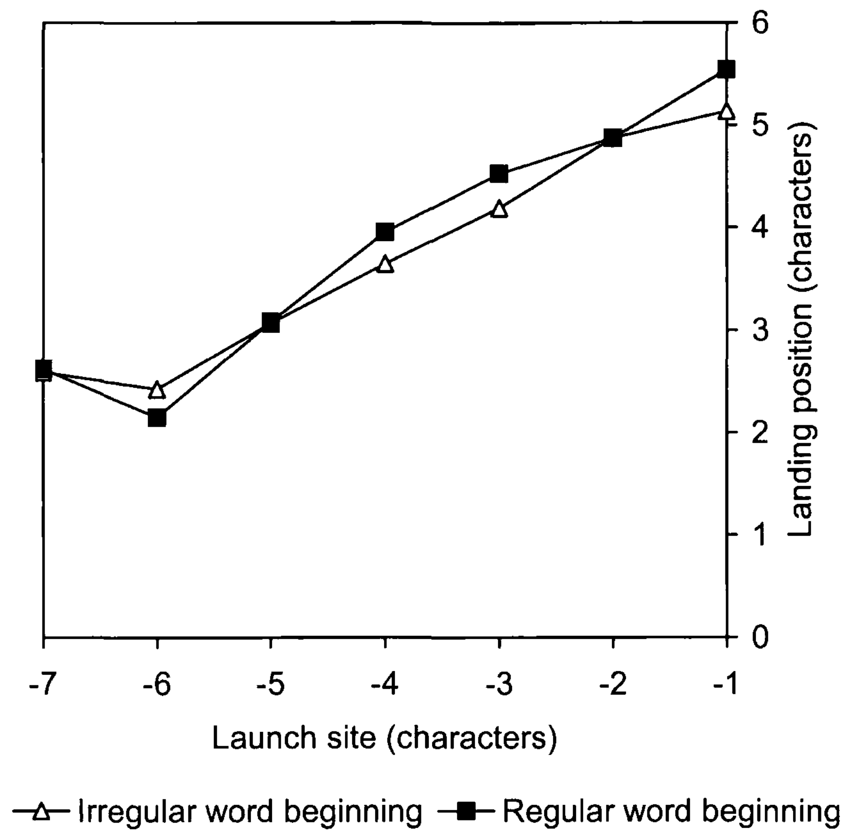

Figure 4.2 Experiment 4. Mean landing position on the critical word for each condition as a function of launch site.

Refixations. Table 4.4 shows the probability of skipping or making one or more than one fixation on the critical word on first pass. Table 4.5 shows the probability of refixating the critical word for those cases in which a first pass fixation was made on the critical word. The irregular words were significantly more likely to be fixated more than once on first pass, $t_1(43) = 6.27, p < .01$; $t_2\ (23) = 6.06, p < .01$. Similar to the reading time measures, the greater probability of refixating the orthographically irregular words suggests that these were more difficult to process once they were fixated.

Table 4.5 *Experiment 4. For Cases in Which the Critical Word was Fixated on First Pass: Probability of Refixating the Critical Word. Frequency of First Refixating to the Left of the Initial Fixation on the Critical Word. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 4	Regular	Irregular
Refixation probability	0.35 (0.16)	0.48 (0.22)
Leftward refixation probability	0.26 (0.24)	0.39 (0.25)
Rightward saccade length	5.1 (2)	4.6 (1.8)
Rightward landing position	6.8 (1.6)	6.6 (1.7)

For those trials in which multiple first pass fixations occurred on the critical word, Table 4.5 shows the probability of making a first refixation to the left of the initial fixation position. First refixations were significantly more likely to be to the left of the initial fixation position if the word had an irregular, rather than regular, word beginning, $t_1(43) = 3.96, p < .01$; $t_2(23) = 3.48, p < .01$. Table 4.5 also shows the length and position of initial rightward refixation saccades on the critical word. Rightward refixation saccades were significantly shorter on orthographically irregular words[1], $t_1(41) = 3.05, p < .01$; $t_2(23) = 2.44, p = .02$. Rightward refixation saccades also landed numerically nearer the word beginning for irregular than regular beginning words but the difference was not significant, $t_1(41) = 1.85, p = .072$; $t_2(23) = 1.02, p = .321$. Therefore the orthographic regularity of the fixated word influenced not only the position of the first fixation on words, but also the direction and length of refixation saccades.

4.1.3: Discussion

First fixation positions were significantly nearer the beginning of orthographically irregular than regular beginning words for saccades launched from or

[1] In Experiment 4, the participants analyses for rightward refixation saccade lengths and positions were based on the data of 42 readers because two participants did not make rightward refixations on the critical word in both conditions.

nearer than the previous word. That is, whilst fixating on word n-1, the initial letter sequence of the critical word was preprocessed and the familiarity of those letters sequences influenced saccade programming. The results are consistent with the finding in Experiment 1 (Chapter 2) that words with orthographically irregular misspellings produce first fixation landing positions nearer the word beginning than correctly spelled words. The results also support previous sentence reading studies undertaken in languages other than English which suggested that orthography can influence where words are first fixated (Hyönä, 1995; Radach et al., 2003; Vonk et al., 2000). However previous sentence reading experiments of the effect of orthography on fixation positions did not appear to control for individual letter frequency. Therefore the effects in these studies might be explained by non-foveal preprocessing of either individual letters or letter sequences frequencies. In contrast, in Experiment 4 individual letter frequency was carefully controlled and so the effects must be explained by preprocessing of letter sequence frequencies rather than individual letter familiarity.

The effects of orthography on fixation positions hold for cases in which single fixations are made on the critical word. Therefore the modulation of saccades must be due to saccade targeting to the word itself rather than a side effect of preprogramming of refixations. That is, if orthography influenced the probability of preprogramming refixations on words, and if preprogramming of refixations caused initial fixations to be directed nearer the word beginning, then this might explain why initial fixation positions are nearer the beginning of irregular beginning words. However, the fact that the effects hold for single fixation cases on the critical word demonstrates that orthography influences initial fixation positions independent of the programming of refixations. Similarly, it might be argued that the effects of orthography on rightward refixation saccade lengths could be due to a greater likelihood of preprogramming of more than two refixations on the orthographically irregular words. However, the effects of orthography on rightward refixation saccade lengths also held for cases in which exactly two first pass fixations were made on the critical word (ts > 2.4, ps $<$ .05). Therefore, the effects of the characteristics of the critical word on rightward refixation saccade lengths are also independent of the nature of refixation programming.

As detailed in Section 1.3.3, a number of possible explanations have been proposed to explain how preprocessing of orthography might influence landing positions. The fact that saccade lengths were numerically shorter for the orthographically irregular condition compared to the correctly spelled condition is consistent with both attraction (Beauvillain et al., 1996; Findlay & Walker, 1999; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) and general linguistic processing (Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992) based explanations. However, the effects of saccade length were not significant and the numerical differences in saccade length were not equal to the differences in landing position. This raises the possibility that differences in launch site may also have contributed to the differences in landing position. However, there were no significant effects of launch site, and no effects of orthography on the probability of skipping or refixating word n-1 directly before fixating the critical word (see Section 1.3.3 or 2.2.3 for an explanation of how fixation probabilities might influence fixation positions). Furthermore, the same trends for the effects of orthography on landing position held for cases in which a single fixation was made on word n-1 directly before fixating the critical word. Therefore, if launch site contributed to the landing position effects it is not clear how this occurred. Nevertheless, the numerical mean differences suggest that both saccade lengths and launch sites seem to contribute to the differences in landing positions (see Table 4.3).

Experiment 4 also showed that refixations are more likely to be directed to the left of the initial fixation position, and rightward refixation saccade lengths are shorter, for orthographically irregular than regular beginning words. These results show that linguistic processing, at least at the level of orthographic regularity, influenced the direction and length of refixation saccades. The results support previous studies that have shown that orthography, or the distribution of information within words, can influence the location (Pynte, 1996, 2000; Pynte et al., 1991; Underwood et al., 1988; Underwood et al., 1987) and length (Hyönä, 1995; Hyönä et al., 1989; Hyönä & Pollatsek, 1998) of refixation saccades. Importantly, Experiment 4 provides clear evidence that orthography can influence both where words are first fixated and refixated in reading, and current accounts of eye movements in reading do not attempt to explain either of these phenomena (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990).

The orthographically irregular words were more difficult to process than the orthographically regular beginning words, shown by the longer reading times and greater probability of refixations on the irregular words. However, there was no effect of regularity on the duration of the fixation before fixating the critical word. Therefore preprocessing of the characteristics of non-fixated words influenced saccade programming (where the eyes moved) but not processing time on the previous fixation (when the eyes moved). In addition, there were also no effects of orthographic regularity on the probability of skipping or refixating the previous word. That is, the results showed clear evidence of an orthographic influence on fixation positions but no evidence of parafoveal-on-foveal effects on either fixation durations or probabilities. These results are inconsistent with studies claiming to find evidence of parafoveal-on-foveal effects (Inhoff, Radach et al., 2000; Inhoff, Starr et al., 2000; Kennedy, 1998, 2000b; Kennedy et al., in press; Murray, 1998; Murray & Rowan, 1998; Pynte et al., 2003; Kennedy et al., 2002; Underwood et al., 2000) and with parallel processing models of eye movements in reading (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980).

4.2: Experiment 5

Studies of the effects of orthography on fixation positions have presented text mainly in lower case. Note that Radach et al. (in press) used critical words with upper case initial letters because in German all nouns have capital initial letters. The primary purpose of Experiment 5 was to examine whether the visually distinctive nature of lower case text is necessary for preprocessing of non-foveal letter sequences and subsequent modulation of fixation positions by those letter sequences in English. In order to do this, Experiment 5 used the same stimuli as Experiment 4 but half of the sentences were presented in lower case (other than the first letter of the first word) and half entirely in upper case. In addition to determining whether orthographic landing position effects hold for both lower and upper case text, the experiment also provides a valuable opportunity to examine whether the characteristics of eye movements differ more generally when reading lower compared to upper case text, this possibility is explored in Section 4.3. The experiment also provides another test of whether orthographic regularity influences prior fixation durations or probabilities (parafoveal-on-foveal effects). In addition, the experiment raises the question of whether visual or abstract letter sequence processing is the basis for any modulations of fixation positions or eye movement patterns generally.

While Experiment 5 cannot provide a definitive answer to the question of whether visual or abstract letter codes may be the basis of any modulation of fixation positions, it certainly seems more likely that preprocessing of letters to an abstract level might be important if landing position effects are found for both lower and upper case text. That is to say, since the sentences are identical other than the case that they are presented in, then there is no difference in the nature of the abstract codes in the lower and upper case conditions. However, reduced exposure to upper case text on the part of the reader might produce less sensitivity to differences in the visual familiarity of upper case letter sequences than is the case for lower case text. Therefore if abstract codes are involved in preprocessing then there should be no difference in the size of landing position effects for lower and upper case text. However, if visual familiarity is important, then there might be an interaction such that for visually familiar lower case text there is a difference in landing position, but for visually less familiar upper case text no difference in landing positions should occur. Such results would be consistent with Findlay and Walker's (1999) visual familiarity based account of orthographic landing position effects.

However if minimal exposure to text is all that is required for development of a sensitivity to non-foveal visual orthographic familiarity, then it is at least possible that visually driven landing position effects might occur regardless of case. Nevertheless, it might be argued that similar landing position effects for both upper and lower case text is more suggestive of abstract preprocessing on the basis that exposure is generally much lower for upper compared to lower case text. Furthermore, regardless of whether non-foveal letter sequences are processed visually or with abstract codes, the important strength of Experiment 5 is that it categorically tests whether the greater visual distinctiveness of lower case text is a necessary condition for letter sequences to influence fixation positions.

Lower case letters have ascenders and descenders that provide visually distinctive letter shape cues for identification. As explained in Section 1.3.3, Reichle, Rayner, and Pollatsek (in press) suggested that low spatial frequency information, such as the presence or absence of ascenders and descenders, might influence saccade programming. Reichle et al. do not specify exactly what influence this information would have on where words are fixated. It is possible that the source of orthographic influences on landing positions may be the low spatial frequency visual characteristics of lower case text, such as the presence of ascenders or descenders. Such visually distinctive features might be crucial to non-foveal processing of letter sequence familiarity, and might be necessary for the oculomotor control system to modulate landing positions according to orthography. Experiment 5 examines whether orthographic regularity influences fixation positions when visually distinctive letter shape cues, which are available in lower case text, are removed. If the effects hold for upper case text then this will demonstrate that processing of letter sequence frequencies does not depend on processing of the highly visually distinctive low spatial frequency letter shape features that are unique to lower case text.

Doré and Beauvillain (1997) and Beauvillain and Doré (1998) showed that the frequency of word initial letter sequences influences where upper case words are first fixated in artificial tasks. These results suggest that the more visually distinctive low spatial frequency letter shape characteristics of lower case text are not necessary for non-foveal preprocessing of letter sequence frequencies. However, as explained in Section 1.3.1, Beauvillain and Doré used artificial tasks in which launch position was highly controlled and normal sentence comprehension processes were unnecessary. It is possible that with the added variables and demands on processing resources in natural reading situations, it might only be possible to process non-foveal letter sequence frequencies in visually distinctive lower case text. Therefore it is important to test whether orthography influences initial fixation positions on upper case text in sentence reading. Hence Experiment 5 will examine whether orthography influences where words are first fixated in lower and upper case text using a natural reading methodology.

If the more visually distinctive nature of lower case letters is necessary to enable non-foveal processing of orthographic regularity in natural sentence reading, then there should be an interaction between orthography and case on the initial fixation positions on the critical word. First fixation landing positions should be nearer the word beginning for irregular words for the lower case text because the lower case text provides visually distinctive letter shapes. In contrast, there should be no difference in landing positions between orthographically regular and irregular beginning words for the upper case text because the upper case letters are not so visually distinctive. In contrast, if the more visually distinctive nature of lower case letters is not necessary to enable non-foveal processing of orthographic regularity in natural sentence reading, then there should be a main effect of orthography and no interaction between orthography and case. That is, the first fixation positions should be nearer the word beginning of orthographically irregular than regular beginning words to the same extent for both lower and upper case text.

4.2.1: Method

Participants. Sixty native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected to normal vision, none had participated in Experiment 4 and all were naïve in relation to the purpose of the experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Materials and Design. The stimuli were identical to those in Experiment 4 except that half were presented in lower case (except for the first letter of the first word) or entirely in upper case. The variables of orthography (regular, irregular) and case (lower, upper) were manipulated within participants and items.

Four lists of 72 sentences were constructed and 15 participants were randomly allocated to each list. Each list included all 48 experimental sentences and 24 filler sentences. Lower and upper case experimental and filler sentences were inter-mingled throughout the lists. Case and orthography were manipulated across the four lists following a Latin square design. Within each list the sentences were presented in a fixed random order with four filler sentences at the beginning. Twenty-four of the sentences were followed by a comprehension question.

Procedure. The procedure was the same as for Experiment 1. Participants were instructed to understand the sentences to the best of their ability. The entire experiment lasted approximately 30 minutes and participants were given one break.

Analyses. The analyses were the same as in Experiment 1. Five percent of trials were excluded due to either no first pass fixations on the first region or tracker loss or blinks on first pass reading of word n-1 or the critical word.

4.2.2: Results

Reading measures were calculated as in Experiment 1. Repeated measures analyses of variance (ANOVAs) were undertaken for the variables of orthography (regular, irregular) and case (upper, lower) with participants (F_1) and items (F_2) as random variables. The mean error rate on the comprehension questions was seven percent, indicating that participants properly understood most of the sentences.

Table 4.6 *Experiment 5. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical Word (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical Word (≤3). Standard Deviations in Parentheses.*

Experiment 5		Word n-1		Fixation n-1		
Case	Orthography	FF	GD	All	n-1	≤3
Lower	Regular	258 (78)	288 (109)	251 (82)	255 (77)	246 (79)
	Irregular	254 (72)	280 (101)	249 (74)	252 (73)	245 (75)
Upper	Regular	255 (77)	279 (103)	253 (78)	259 (78)	254 (75)
	Irregular	261 (79)	289 (110)	255 (81)	259 (81)	264 (92)

Parafoveal-on-foveal effects. Table 4.6 shows the mean reading time measures on word n-1 and mean fixation durations prior to fixating the critical word. There were no significant effects of regularity on first fixation durations on word n-1 or gaze durations on word n-1 (F's < 1) and no reliable interactions between orthography and case for either first fixation durations, F_1 (1, 59) = 3.86, p = .05, MSE = 400, F_2 (1, 23) = 1.9, p = .181, MSE = 288, or gaze durations, F_1 (1, 59) = 9.63, p < .01, MSE = 523, F_2 (1, 23) = 2.63, p = .118, MSE = 731, on word n-1. There were no significant effects of orthography and no interaction between orthography and case on the duration of the fixation prior to first fixating the critical word for all of the data, for saccades launched from word n-1 and for saccades launched from three or less characters from the critical word (F's < 1.2). Therefore similar to all of the Experiments presented so far, the word initial letter sequences of the critical word did not influence fixation durations until the critical words were directly fixated.

Table 4.7 *Experiment 5. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical Word and Word n+1. Fixation Duration after Leaving the Critical Word (Fix. n+1). Standard Deviations in Parentheses.*

Experiment 5		Critical Word			Fix.	Word n+1		
Case	Orthography	FF	GD	TT	n+1	FF	GD	TT
Lower	Regular	296 (106)	366 (163)	488 (307)	266 (77)	271 (84)	287 (102)	352 (201)
	Irregular	338 (145)	498 (302)	637 (426)	260 (89)	261 (89)	279 (106)	333 (183)
Upper	Regular	299 (104)	378 (189)	510 (320)	270 (86)	277 (88)	292 (101)	360 (189)
	Irregular	336 (145)	490 (297)	655 (434)	265 (85)	269 (85)	285 (121)	350 (209)

Reading time measures. Table 4.7 shows the mean reading time measures on the critical word for each condition. Mean first fixations, F_1 (1, 59) = 64.57, p < .01, MSE = 1469, F_2 (1, 23) = 29.46, p < .01, MSE = 1247, gaze durations, F_1 (1, 59) = 75.58, p < .01, MSE = 11675, F_2 (1, 23) = 53.33, p < .01, MSE = 6681, and total time, F_1 (1, 59) = 75.49, p < .01, MSE = 17047, F_2 (1, 23) = 32.04, p < .01, MSE = 16070, were significantly longer on irregular than regular beginning words. There were no effects of case on either first fixations or gaze durations on the critical word (F's < 1). There were no reliable differences in total reading time for upper case compared to lower case critical words, F_1 (1, 59) = 3.84, p = .06, MSE = 6349, F_2 (1, 23) = 2.52, p = .126, MSE = 3389. For all three reading time measures there were no significant interactions between orthography and case (F's < 1.5). Therefore, as in Experiment 4, reading times were longer on the orthographically irregular words.

Table 4.7 also shows the mean reading times after leaving the critical word. There was no effect of orthography on the duration of the fixation after leaving the critical word, F_1 (1, 59) = 3.43, p = .069, MSE = 524, F_2 (1, 23) = 2.73, p = .112, MSE = 255, and no interaction between case and orthography (F's < 1). First fixations on word n+1 were significantly longer when preceded by orthographically regular than irregular beginning words, F_1 (1, 59) = 8.56, p < .01, MSE = 864, F_2 (1, 23) = 4.89, p = .04, MSE = 416, there were no reliable effects for gaze durations, F_1 (1, 59) = 4.27, p = .04, MSE = 1119, F_2 (1, 23) = 2, p = .171, MSE = 621, and no effects of orthography on total time on word n+1, F_1 (1, 59) = 2.65, p = .109, MSE = 3039, F_2 (1, 23) = 2.88, p = .103, MSE = 1561. There were no interactions between orthography and case for any of the reading time measures on word n+1 (F's < 1). Therefore the only reliable spillover effect was longer first fixation durations on word n+1 when the critical word was orthographically regular compared to when it was orthographically irregular. The direction of this effect is opposite to a standard spillover effect, that is, when the critical word was more difficult to process, fixations were shorter, not longer on the following word. Perhaps the longer fixations on the critical word allowed more time for sentence comprehension processes which facilitated processing on the following word.

Table 4.8 *Experiment 5. Mean Landing Positions, Incoming Saccade Extents and Launch Sites. Standard Deviations in Parentheses.*

Experiment 5	Case	Orthography	Landing position	Saccade extent	Launch site
All data	Lower	Regular	3.9 (2.1)	8.4 (2.5)	4.5 (2.8)
		Irregular	3.7 (2)	8.2 (2.1)	4.4 (2.4)
		Difference	0.2	0.2	0.1
	Upper	Regular	3.9 (2.1)	8.5 (2.7)	4.7 (3.0)
		Irregular	3.8 (2.1)	8.3 (2.5)	4.5 (2.8)
		Difference	0.1	0.2	0.2
Launch word n-1	Lower	Regular	4.3 (1.8)	7.9 (1.7)	3.5 (1.6)
		Irregular	4.1 (1.8)	7.8 (1.6)	3.7 (1.6)
		Difference	0.2	0.1	-0.2
	Upper	Regular	4.24 (1.9)	7.9 (1.7)	3.7 (1.6)
		Irregular	4.2 (1.9)	7.8 (1.8)	3.6 (1.6)
		Difference	0.04	0.1	0.1
Launch ≤3 characters	Lower	Regular	5.2 (1.5)	7.3 (1.5)	2.1 (0.8)
		Irregular	5.0 (1.4)	7.2 (1.4)	2.2 (0.8)
		Difference	0.2	0.1	-0.1
	Upper	Regular	5.2 (1.5)	7.3 (1.5)	2.2 (0.8)
		Irregular	4.9 (1.6)	7.1 (1.6)	2.2 (0.8)
		Difference	0.3	0.2	0

Landing positions. Table 4.8 shows the mean landing positions on the critical word for Experiment 5. For all of the data, mean first fixation landing positions on the critical word were 0.2 characters nearer the word beginning for lower case text and 0.1 characters nearer the word beginning for upper case text but these effects were not significant, F_1 (1, 59) = 2.74, p = .103, *MSE* = 0.35, F_2 (1, 23) = 2.7, p = .114, *MSE* = 0.13. There were also no significant effects of case (F's < 1) and no interaction between orthography and case, F_1 (1, 59) = 1.5, p = .225, *MSE* = 0.26, F_2 (1, 23) = 1.77, p = .196, *MSE* = 0.13. Figure 4.3 shows the distribution of landing positions for lower case text and Figure 4.4 shows the distribution of landing positions for upper case text. The preferred viewing positions are shifted to the left for orthographically irregular beginning words for both upper and lower case text.

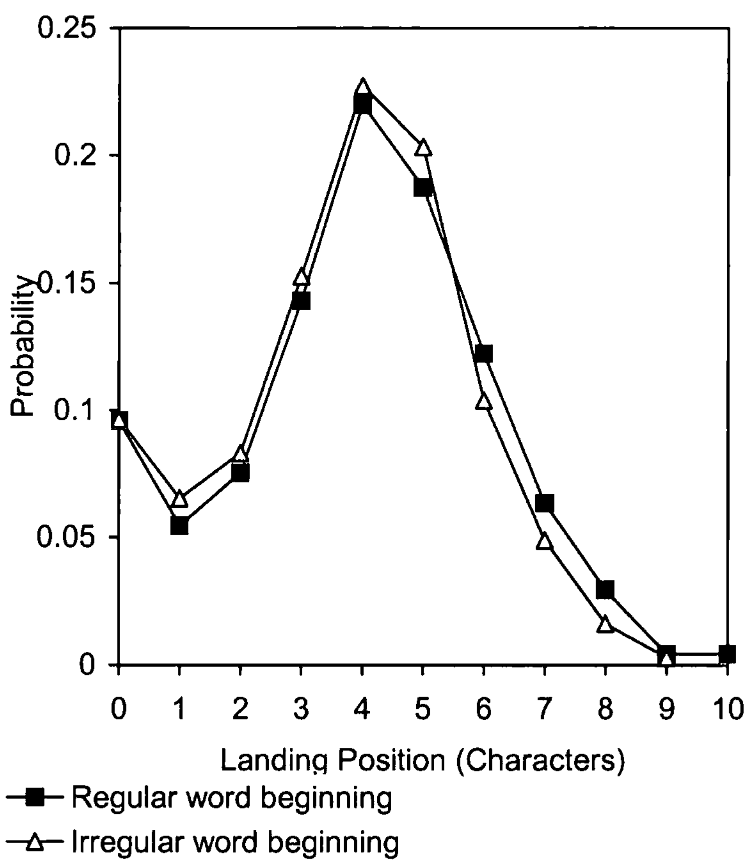

Figure 4.3 Experiment 5. First fixation landing position distributions on the critical word for lower case text. Landing position zero is the space before the word and landing position one is the first letter of the word.

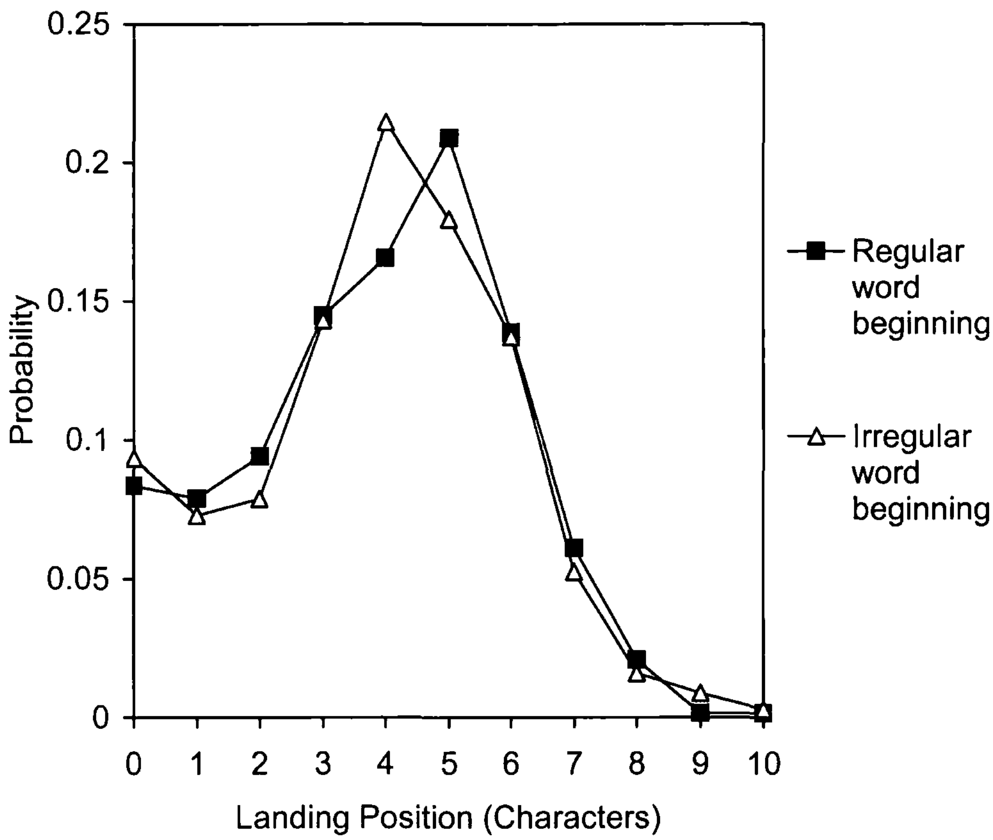

Figure 4.4 Experiment 5. First fixation landing position distributions on the critical word for upper case text. Landing position zero is the space before the word and landing position one is the first letter of the word.

Similar to Experiment 4, the landing position effects were analysed as a function of launch site because saccades launched from distant launch sites might not be influenced by non-foveal orthography due to degradations in visual acuity. When the analyses were restricted to the 84 percent of saccades launched from word n-1, the mean first fixation position was significantly nearer the word beginning for irregular than regular beginning words, F_1 (1, 59) = 5.94, p = .02, *MSE* = 0.28, F_2 (1, 23) = 4.64, p = .04, *MSE* = 0.11, there was no significant effect of case (F's < 1) and no significant interaction between orthography and case, F_1 (1, 59) = 2.7, p = .106, *MSE* = 0.41, F_2 (1, 23) = 2.35, p = .139, *MSE* = 0.13. Although there was no significant interaction, the mean landing positions for saccades launched from word n-1 do suggest a larger difference in fixation positions for lower (0.2) than upper (0.04) case text. However, when the analyses were restricted to the 40 percent of saccades launched from three characters before the critical word, mean first fixation landing positions were 0.2 characters significantly nearer the beginning of irregular beginning words for lower case text and 0.3 characters significantly nearer the beginning for upper case text, F_1 (1, 59) = 3.89, p = .05, MSE = 0.39, F_2 (1, 23) = 19.5, p < .01, MSE = 0.07. There were no effects of case (F's < 1) and there was no interaction between orthography and case (F's < 1). Therefore, for very near launch sites the effect of orthography is clearly the same for both upper and lower case text.

Similar to Experiment 4 the results show that, for near launch sites, first fixation positions land nearer to the beginning of lower case orthographically irregular, compared to regular, beginning words. Importantly, the same effect was found for upper case text. Consequently the use of non-foveal orthography to modulate first fixation positions on words does not depend on the greater visual distinctiveness of lower case text compared to upper case text. Also, there was no effect of case on landing positions, suggesting that any differences between lower and upper case text (such as visual distinctiveness) did not influence fixation positions.

Incoming saccade extent and launch site. Table 4.8 shows the mean launch sites prior to and saccade lengths into the critical word. For all the data, there were no effects of orthography, F_1 < 1, F_2 (1, 23) = 1.46, p = .239, MSE = 0.16, case, F_1 (1, 59) = 1.69, p = .199, MSE = 0.61, F_2 (1, 23) = 1.26, p = .273, MSE = 0.31, and no interaction between orthography and case (F's < 1) on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word were significantly shorter for irregular than regular beginning words, F_1 (1, 59) = 6.43, p = .01, MSE = 0.43, F_2 (1, 23) = 6.69, p = .02, MSE = 0.17. There were no effects of case, F_1 (1, 59) = 2.76, p = .102, MSE = 0.43, F_2 (1, 23) = 1.49, p = .235, MSE = 0.29, and no interaction between orthography and case (F's < 1). For saccades launched from word n-1, there were no effects of orthography (F's < 1.3), case, (F's < 1) and no interaction between orthography and case, F_1 (1, 59) = 3.43, p = .069, MSE = 0.30, F_2 (1, 23) = 2.49, p = .128, MSE = 0.12, on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word were numerically shorter for irregular than regular beginning words, F_1 (1, 59) = 1.85, p = .179, MSE = 0.25, F_2 (1, 23) = 3.54, p = .073, MSE = 0.09, there were no effects of case (F's < 1) and no interaction between orthography and case (F's < 1). For saccades launched from three or less characters from the beginning of the critical word, there were no effects of orthography, $F_1 \leq 1$, F_2 (1, 23) = 2.07, p = .164, MSE = 0.06, case, F_1 (1, 59) = 1.53, p = .222, MSE = 0.18, F_2 < 1, and no interaction between orthography and case, F_1 (1,

59) = 3.58, p = .063, MSE = 0.15, $F_2 < 1$, on the mean launch site prior to fixating the critical word. Mean saccade lengths into the critical word were numerically shorter for irregular than regular beginning words, the effect was significant across items, F_2 (1, 23) = 5.21, p = .03, MSE = 0.14, but not participants, F_1 (1, 59) = 1.77, p = .188, MSE = 0.43. There were no effects of case (F's < 1) and no interaction between orthography and case (F's < 1). Although there were no significant effects of orthography on mean launch sites, differences in fixation probabilities prior to fixating the critical word may have influenced launch positions (as explained in Section 1.3.3 and 2.2.3).

Table 4.9 *Experiment 5. Probability of Skipping and Refixating Word n-1 Directly Before Fixating the Critical Word. Probability of Skipping, Making a Single Fixation and Refixating (≥Two) the Critical Word on First Pass. Standard Deviations in Parentheses.*

Experiment 5		Word n-1 skip	Word n-1 refixation	Critical word fixation probabilities		
Case	Orthography			Skip	Single	≥Two
Lower	Regular	0.17 (0.14)	0.12 (0.12)	0.01 (0.04)	0.73 (0.22)	0.26 (0.22)
	Irregular	0.16 (0.13)	0.09 (0.11)	0.01 (0.04)	0.59 (0.21)	0.4 (0.22)
Upper	Regular	0.15 (0.14)	0.1 (0.12)	0.01 (0.03)	0.72 (0.19)	0.27 (0.2)
	Irregular	0.15 (0.16)	0.11 (0.14)	0.01 (0.03)	0.61 (0.21)	0.38 (0.22)

Table 4.9 shows the probability of skipping and refixating word n-1 directly before fixating the critical word. There were no effects of orthography, F_1 (1, 59) = 1.4, p = .242, MSE = 107, F_2 (1, 23) = 1.27, p = .271, MSE = 41, case (F's < 1) and no interactions between orthography and case (F's < 1) for the probability of skipping word n-1 before fixating the critical word. There were also no effects of orthography (F's < 1), case (F's < 1.3) and no reliable interaction between orthography and case, F_1 (1, 59) = 4.34, p = .04, MSE = 55, F_2 (1, 23) = 2.9, p = .102, MSE = 37, for the probability of refixating word n-1 before fixating the critical word.

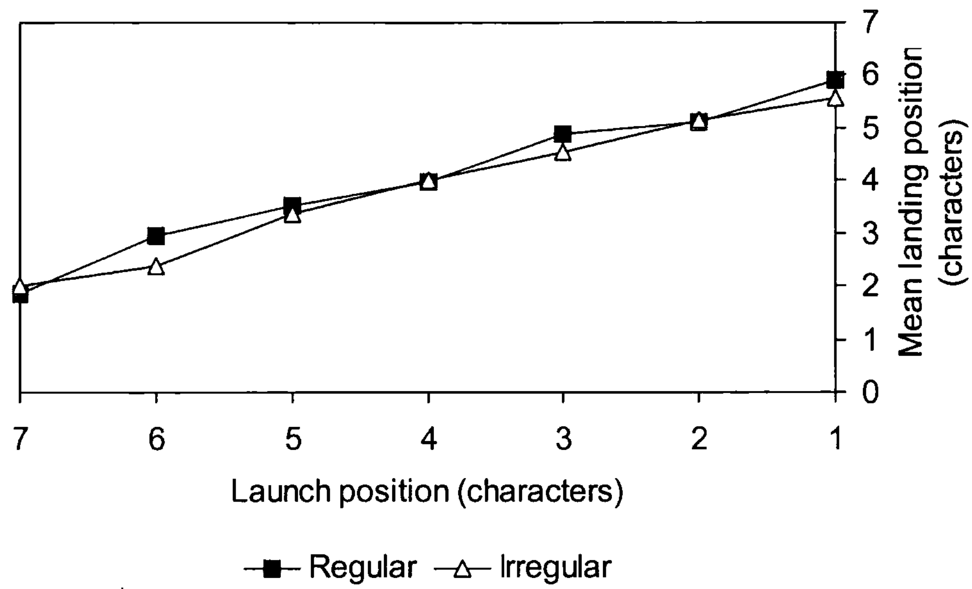

Figure 4.5 Experiment 5. Mean landing position on the critical word for each launch position for orthographically regular and irregular beginning words for lower case text.

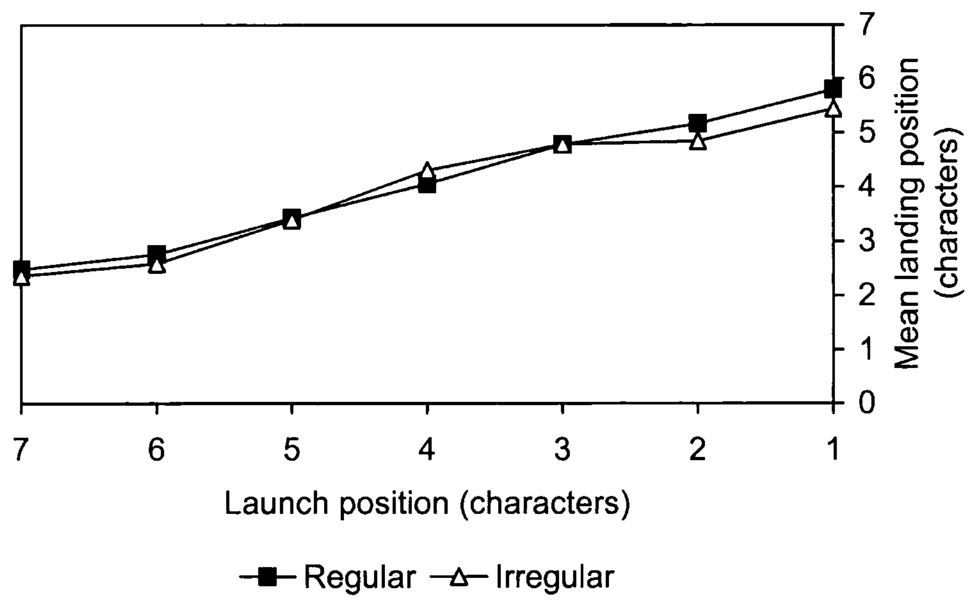

Figure 4.6 Experiment 5. Mean landing position on the critical word for each launch position for orthographically regular and irregular beginning words for upper case text.

For all of the data saccades into the critical word are shorter for orthographically irregular words, regardless of case. A similar pattern holds for saccades launched from word n-1 and from three or less characters from the beginning of word n, although these results are not reliable. In addition, Figures 4.5 and 4.6 show that the mean landing positions are numerically nearer the beginning of the critical word for orthographically irregular compared to regular beginning words regardless of launch site for both lower and upper case text. The results therefore suggest that the more visually distinctive characteristics of lower case text, compared to upper case text, are not necessary in order for non-foveal orthography to influence saccade extent. In contrast there were no significant effects of launch site or prior fixation probabilities and no consistent pattern in the direction of the effects for each of the launch site analyses.

Refixations. Table 4.9 shows the probability of refixating on the critical word. Table 4.10 shows the probability of refixating on the critical word for those cases in which a first pass fixation was made on the word. For those cases in which a first pass fixation was made on the critical word, the irregular beginning words were more likely to be fixated more than once on first pass than the regular beginning words, F_1 (1, 59) = 46.18, $p < .01$, $MSE = 190$, F_2 (1, 23) = 27.48, $p < .01$, $MSE = 131$, there were no effects of case and no interaction between orthography and case (F's < 1). Similar to the reading time measures, the greater probability of refixating the orthographically irregular words suggests that these were more difficult to process once they were fixated.

Table 4.10 *Experiment 5. For Cases in Which the Critical Word was Fixated on First Pass: Probability of Refixating the Critical Word. Probability of First Refixating to the Left of the Initial Fixation on the Critical Word. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 5	Lower case		Upper case	
	Regular	Irregular	Regular	Irregular
Refixation probability	0.27 (0.22)	0.4 (0.22)	0.27 (0.2)	0.38 (0.22)
Leftward refixation probability	0.23 (0.32)	0.31 (0.29)	0.22 (0.27)	0.39 (0.31)
Rightward saccade length	5.3 (1.9)	4.6 (1.9)	5.2 (1.8)	4.9 (1.8)
Rightward landing position	7.1 (1.6)	6.7 (1.6)	7 (1.7)	6.8 (2)

For those trials in which multiple first pass fixations occurred on the critical word, Table 4.10 shows the probability of making a first refixation to the left of the initial fixation. Refixations tended to be more likely to be to the left of the initial fixation position for irregular than regular beginning words, the effect was significant across items, $F_2\,(1, 23) = 7.65, p = .01, MSE = 384$, but not participants, $F_1\,(1, 50) = 3.12, p = .083, MSE = 1368$. There were no effects of case (F's < 1) and no interactions between orthography and case[2], $F_1\,(1, 50) = 3.67, p = .061, MSE = 587$, $F_2\,(1, 23) = 1.62, p = .216, MSE = 335$. Table 4.10 also shows the length and position of initial rightward refixation saccades on the critical word. The mean rightward refixation saccade lengths were significantly shorter in the irregular than regular word beginning conditions, $F_1\,(1, 36) = 4.8, p = .04, MSE = 1.2$, $F_2\,(1, 23) = 8.76, p < .01$, $MSE = 0.8$. There were no effects of case (F's < 1.8) and no interaction between orthography and case (F's < 1). The mean rightward refixation landing positions were numerically nearer the word beginning for irregular than regular beginning words but these differences were not significant[3], $F_1\,(1, 36) = 1.5, p = .229, MSE = 1$, $F_2\,(1, 23) = 3.37, p = .08, MSE = 0.8$, there were no effects of case and no interactions between orthography and case (F's < 1). These analyses show that for both upper and lower case text, orthography tends to influence the direction of refixation saccades and significantly influences the length of refixation saccades. The results for upper case text demonstrate that the effects of orthography on refixations in Experiment 4 did not depend on the more visually distinctive characteristics of lower compared to upper case text.

4.2.3: Discussion

Experiment 5 showed that for both upper and lower case text, first fixation landing positions were nearer the beginning of orthographically irregular beginning words for saccades launched from near launch sites. Saccade lengths were shorter into

---

[2] In Experiment 5, the participants analyses for refixation probabilities were based on the data of 51 readers because nine readers did not produce data for refixations on the critical word in all four of the conditions.

[3] In Experiment 5, the participants analyses for rightward refixation saccade lengths and positions were based on the data of 37 readers because twenty-three participants did not produce data for rightward refixations on the critical word in all four of the conditions.

irregular than regular beginning words. Therefore, in support of both attraction (Beauvillain et al., 1996; Findlay & Walker, 1999; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) and general linguistic processing (Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992) based explanations, Experiment 5 suggests that the landing position effects are at least partly modulated by differences in saccade length. Similar to Experiment 4, refixation directions and positions were also influenced by the orthography of the fixated word for both upper and lower case text. Furthermore, there were no parafoveal-on-foveal effects on either prior fixation durations or probabilities.

The finding that orthography influences where words are fixated for words presented in upper case text supports similar results shown in artificial tasks (Beauvillain & Doré, 1998; Doré & Beauvillain, 1997). These results indicate that the effects of orthography for lower case text in Experiments 1 and 4 are not dependent on the greater visual distinctiveness (e.g. presence of ascenders and descenders) of lower case text compared to upper case text. Reichle et al. (in press) suggested that low spatial frequency information, such as spaces between words and the presence or absence of ascenders and descenders, might influence saccade programming. Although the model simulates the effect of word length on fixation positions, it does not specify exactly what influence features such as ascenders would have on where words are fixated. It seems unlikely that low spatial frequency features, such as ascenders and descenders, could be used to modulate initial fixation positions in upper case text. Therefore, although processing of low spatial frequency letter shape information might possibly explain the influence of orthography on landing positions in lower case text it seems doubtful that such visual processing might also explain landing position effects in upper case text.

As explained in the Introduction to Section 4.2, there is also a debate as to whether the influence of orthography on saccade programming might be explained by visual or abstract non-foveal preprocessing. Findlay and Walker's (1999) explanation for the influence of orthography on fixation positions is based on visual processing of familiarity (see Section 1.3.2). Although Experiment 4 can not definitively show whether the effects are due to visual or abstract preprocessing, the fact that the effects hold for both lower and upper case text are certainly consistent with an abstract preprocessing explanation. See Section 4.3.2 for further discussion of this issue.

4.3: Global Effects of Case in Experiment 5

Experiment 5 provides an opportunity to examine whether eye movement reading patterns are generally different when reading lower compared to upper case text. That is, whether the reduced visual distinctiveness or familiarity of upper case compared to lower case text has any effect on oculomotor behaviour as indexed by general reading measures. The only study to examine eye movements in the reading of sentences presented entirely in upper case was undertaken by Tinker and Paterson in 1939 (for a discussion of this work see also: Morrison & Inhoff, 1981; Paterson & Tinker, 1946, 1947). Tinker and Paterson used a photographic technique to record eye movements whilst participants read ten paragraphs of text in either lower or upper case. The upper case text covered 35 percent larger area than the lower case text and there seems to have been no control over viewing distance between subjects.

Tinker and Paterson (1939) reported that fixation durations were 20ms shorter for upper case text and there was no difference in regression frequency. However there were 12 percent more fixations and consequently total reading times were seven percent longer. Although the longer reading times might indicate that upper case text is more difficult to read than lower case text, the results are confounded by differences in the size of the text. Text size certainly had an effect on saccade lengths. Paterson and Tinker (1947) reported that there were 14 percent fewer characters per fixation (saccades covered a smaller amount of text) but the mean picas per fixation increased by 34 percent (saccades covered a larger physical distance) for upper case text. More recent studies of eye movements in reading of different sized text suggests that larger text produces physically larger saccades which subtend the same number of characters as smaller text (Morrison, 1983, Morrison & Rayner, 1981; O'Regan, 1983; O'Regan et al., 1983). It is not clear from Tinker and Paterson's study whether saccades in upper case text subtended fewer characters because the text was in upper case or because the text was simply so large that, due to acuity limitations, fewer characters could be processed on each fixation. The fact that the average fixation durations were shorter for upper case text might suggest that less linguistic processing was undertaken on each fixation.

To summarise, Tinker and Paterson (1939) showed that upper case text produced longer overall reading times than upper case text. However, it is possible that the longer reading times were due to greater processing difficulty due to acuity (text size) of upper case text rather than reduced visual distinctiveness or familiarity of upper compared to lower case text. Tinker and Paterson's study was undertaken over sixty years ago and eye movement recording and analysis methods have improved considerably during this time. In Experiment 5 viewing distance was controlled and lower and upper case characters subtended the same degrees of visual angle. If eye movement patterns differ between lower and upper case text in this experiment then this will indicate that the visual distinctiveness, or familiarity, of text influences reading.

4.3.1: Results

A number of general reading measures were used to examine the effects of case including total sentence reading time, number of fixations, mean forward and regressive fixation durations, number of regressions, and mean forward and regressive saccade lengths. Paired samples *t*-tests were undertaken with participants (t_1) and items (t_2) as random variables.

Tinker and Paterson (1939) found that total sentence reading times were seven percent longer for upper case text. However in the present experiment total sentence reading times (including both fixations and saccades) were just two percent longer for upper ($M = 3870$, $SD = 1555$) than lower ($M = 3791$, $SD = 1506$) case text and this difference was marginally significant, t_1 (59) = 1.88, $p = .065$, t_2 (23) = 2.02, $p = .055$. Whereas Tinker and Paterson found that upper case text produced 12 percent more fixations than lower case text, there was no difference in the number of fixations between upper ($M = 12.8$, $SD = 4.4$) and lower ($M = 12.6$, $SD = 4.3$) case text (t's < 1.5, ps > .16) in the present experiment. Furthermore, in contrast to Tinker and Paterson who found that average fixation durations were 20ms shorter for upper than lower case text, in the current experiment there were no differences in either forward fixation durations, (Upper case: $M = 259$, $SD = 53$; Lower case: $M = 256$, $SD = 53$) t_1 (59) = 1.93, $p = .058$, t_2 (23) = 1.68, $p = .106$, or regressive fixation durations, (Upper case: $M = 250$, $SD = 90$; Lower case: $M = 255$, $SD = 100$) (t's < 1.4, $ps > .19$). Although Tinker and Paterson found no effects of regression frequency, in this experiment there tended to be slightly more regressions for upper ($M = 2.4$, $SD = 2.2$)

compared to lower (M = 2.3, SD = 2.1) case text, t_1 (59) = 2.3, p = .03, t_2 (23) = 2, p = .058. Also, in contrast to Paterson and Tinker (1947) there were no differences in either forward (Upper case: M = 8.3, SD = 1.9; Lower case: M = 8.3, SD = 1.9) (t's < 1) or regressive (Upper case: M = 10.4, SD = 9.5; Lower case: M = 10, SD = 10) (t's < 1) saccade lengths (measured in characters but equivalent to physical saccade size). Overall, these results indicate that there was little difference in eye movement behaviour when participants read text in upper compared to lower case.

4.3.2: Discussion

The effects of case shown in this experiment are quite different to those of Tinker and Paterson (1939). Tinker and Paterson found longer overall reading times due to a greater number of fixations, average fixation durations were actually shorter for upper case text. In contrast, although overall reading times were marginally longer for upper case text in the present experiment, this might be explained by numerically longer average forward fixation durations and a marginally higher number of regressions for the upper compared to lower case text. The differences in results might be explained by the fact that the upper case text covered a larger area than the lower case text in Tinker and Paterson's experiment. Perhaps the larger text reduced the number of characters and words that could be processed on each fixation in the upper case text and participants may have compensated for this by increasing the number of fixations whilst shortening the average fixation durations (due to the reduced linguistic input). In the present experiment, the marginally longer reading times and similar fixation position effects for upper and lower case text suggest that while lower case text might be slightly easier to read because it is more visually distinctive or familiar, very similar processes of oculomotor control are applied regardless of the case the text is presented in.

The fact that there was so little difference in the reading time measures for lower and upper case text suggests that very similar processes are used for reading them. This implies that either abstract letter codes are used to process non-foveal letter sequences, or that both lower and upper case text use visual familiarity of non-foveal text to programme eye movements. However, the fact that exposure to upper case text is generally less than that for lower case text, and yet reading measures for the two are largely the same, certainly lends support to the suggestion that abstract letter codes are involved in non-foveal letter sequence processing and subsequent modulation of fixation positions.

4.4: Further Analyses of Experiments 4 and 5

Together, Experiments 4 and 5 provide data from a total of 104 participants reading a set of highly controlled materials. The data therefore offer a valuable opportunity to examine some basic eye movement phenomena independent of the experimental variables. Three issues were investigated, fixation durations as a function of fixation position (Section 4.4.1), the relationship between prior fixation duration and saccade targeting accuracy (Section 4.4.2) and the relationship between prior fixation duration and subsequent saccade length (Section 4.4.3).

4.4.1: Fixation durations as a function of fixation position

Studies using isolated words have shown that the time to identify words is shorter when words are initially fixated near the middle, or slightly left of the middle, referred to as the "optimal viewing position" (O'Regan & Jacobs, 1992; O'Regan, Lévy-Schoen et al., 1984) (see Section 1.3.2). In normal sentence reading, Vitu et al., 1990) found a similar, but much weaker optimal viewing position pattern and Rayner et al. (1996) and Rayner and Fischer (1996) found no clear effect of fixation location on single fixation durations. In contrast, recent studies have suggested that there might be an inverted optimal viewing position effect such that longer fixation durations occur on fixations nearer the word centre (O'Regan et al., 1994; Hyönä & Bertram, in press b; Radach & Heller, 2000; Vitu et al., 2001). Despite the conflicting evidence, Reichle et al.'s (in press) model predicts a standard optimal viewing position effect, such that fixation durations are shorter when the centre of the word is first fixated. Other accounts of eye movements in reading (Engbert et al., 2002; O'Regan, 1990; Reilly & Radach, 2003; Yang & McConkie, 2001) also use eccentricity as a variable in word processing and so might predict similar effects of fixation location on fixation duration. That is, word processing is faster, and so fixation durations might be shorter, at the word centre because more of the fixated word is available in high acuity vision.

Clearly further evidence is required to help resolve the issue of whether an optimal viewing position effect is shown in fixation durations in normal reading. Experiments 4 and 5 allow the examination of fixation durations in relation to fixation position for five and six letter words (word n-1 and word n+1) and for nine and ten letter words as a function of orthographic regularity (the critical word).

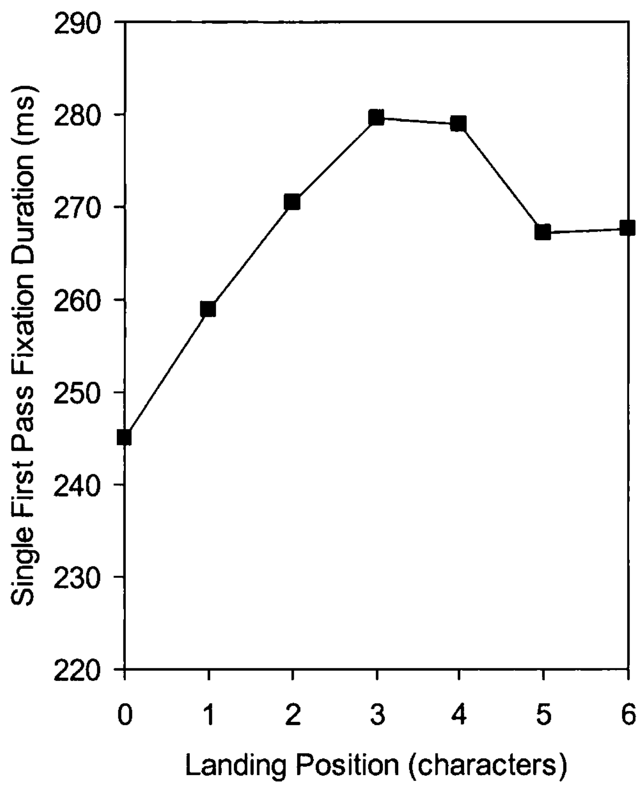

Figure 4.7 Experiments 4 & 5. Mean single first pass fixation durations on five and six letter words as a function of fixation position.

Figure 4.7 shows mean single first pass fixation durations plotted for five and six letter words and Figure 4.8 shows mean single first pass fixation durations plotted for nine and ten letter words. Both Figures 4.7 and 4.8 suggest that single first pass fixation durations are longer when the fixation position is near the word centre for five and six, and nine and ten letter words and for both orthographically regular and irregular beginning words. For the five and six letter words there was a main effect of landing position[4], F_1 (4, 410.9) = 22.27, $p < .01$, $MSE = 926$. Repeated contrasts

[4] For the five and six letter words, an ANOVA was undertaken with six levels of the landing position variable including the space before the word and characters one to five. The sixth character was not included because not all participants fixated this letter. For the analysis of the effect of landing position, the Mauchly test of

comparing each fixation position with the subsequent fixation position showed that single first pass fixations were; longer on the first character than on the space, F_1 (1, 103) = 6.79, p = .01, MSE = 2166; longer on the second character than the first character, F_1 (1, 103) = 9.38, p < .01, MSE = 1351; longer on the third character than the second character, F_1 (1, 103) = 11.11, p < .01, MSE = 653, no different on the third and fourth characters (F_1 < 1); and longer on the fourth character than the fifth character, F_1 (1, 103) = 9.18, p < .01, MSE = 1136. The effects of landing position show that fixation position on five and six letter words influenced single first pass fixation durations. Furthermore, the results suggest that fixations are longer near the word centre, showing an inverted optimal viewing position pattern.

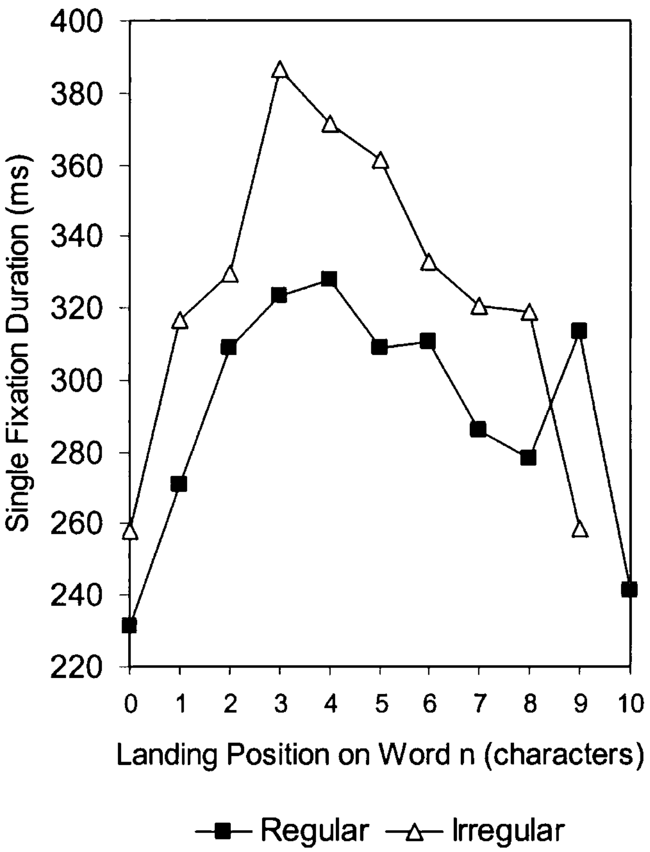

Figure 4.8 Experiments 4 & 5. Mean single first pass fixation durations on nine and ten letter words as a function of fixation position and orthographic regularity.

Single first pass fixation durations on the nine and ten letter words were not analysed statistically as a function of specific landing position because there were

---

sphericity was significant and so the Greenhouse-Geisser Epsilon adjustment was used.

fewer data points (only data from single fixations on the critical word spread over a wider range of possible fixation positions). Consequently the data were grouped into fixations on or just left of the word centre (characters three, four and five) and away from the word centre (the space before the word and all other characters). Mean single fixation durations were significantly longer near the word centre (Regular = 320; Irregular = 373) than away from the word centre (Regular = 294; Irregular = 319), F_1 $(1, 87) = 15.6, p < .01, MSE = 2566$, $F_2\,(1, 23) = 77.92, p < .01, MSE = 486$, and single fixations were longer on irregular than regular beginning words, $F_1\,(1, 87) = 49.34, p < .01, MSE = 4078$, $F_2\,(1, 23) = 25.17, p < .01, MSE = 1378$. There was no reliable interaction between fixation position and regularity[5], $F_1\,(1, 87) = 3.28, p = .074, MSE = 2034$, $F_2\,(1, 23) = 8.32, p < .01, MSE = 673$. Similar to the five and six letter words, the results show an inverted optimal viewing position pattern such that single first pass fixations nearer the word centre are longer than those towards the ends of the word. Furthermore, the main effect of orthographic regularity shows that the characteristics of a word influence fixation durations as well as the fixation position.

To summarise, analyses of both five and six letter words and nine and ten letter words show an inverted optimal viewing position effect on fixation durations, such that single fixation durations are longer nearer the word centre. These results are consistent with previous studies that have shown inverted optimal viewing position effects on single fixation durations (O'Regan et al., 1994; Radach & Heller, 2000; Vitu et al., 2001). Currently there is no clear or widely held view as to which processes induce the inverted optimal viewing position. One possibility is that more fixations landing away from the word centre were intended to land on other words compared to saccades landing on the word centre or preferred viewing position. Corrective saccades might be quickly executed for those cases in which saccades were incorrectly targeted and so fixation durations might be shorter on average for saccades landing away from the word centre. Alternatively, perhaps the ends of words provide poor visual information about the rest of the word. In order to disambiguate the identity of the word, and instead of simply refixating it, the eyes might move quickly to the following word in order to sample potentially constraining information. Clearly

---

[5] The participants analysis for effects of preferred viewing position and regularity on single fixation durations were based on the data of 88 readers because 16 readers did not made single fixations in all four of the conditions on the critical word.

further research is required in order to investigate different possible explanations for the inverted optimal viewing position (see Vitu et al., 2001).

4.4.2: Prior fixation duration and saccade targeting accuracy

The second issue to be addressed was whether prior fixation durations influence the accuracy of saccade targeting (discussed in Section 1.3.1). Findlay (1981) and Coëffé and O'Regan (1987) showed that saccades are targeted more accurately following longer prior fixation durations in basic visual tasks. McConkie et al. (1988) found that for long fixation durations prior to fixating words five to eight characters in length, undershooting from far launch sites and overshooting from near launch sites was reduced such that mean landing positions were more accurately targeted to the left of the word centre (the preferred viewing position). McConkie et al. (1994) claimed to find a similar pattern of results. Similarly, Beauvillain and Doré (1995) found that, in an artificial task in which all saccades were launched from near launch sites, for long prior fixation durations overshooting was reduced such that more fixations landed on the preferred viewing position. Recently Reichle et al. (1999; in press) have incorporated this phenomenon into their model of eye movements in reading. However, this assumption has been largely based on McConkie et al's descriptive data. In contrast, Radach and Heller (2000) failed to find a relationship between prior fixation duration and saccade accuracy in a study of corpus reading data (see also Radach & McConkie, 1998). Therefore it is important to investigate whether there is a relationship between fixation duration and saccade targeting accuracy in other data sets. Consequently, the relationship between the first fixation position on the critical word and the prior fixation duration was investigated for the data collected in Experiments 4 and 5. If the results are consistent with longer prior fixation durations being associated with more accurate saccade targeting then the findings will support McConkie et al. (1988) and Reichle et al's model. However, if no consistent pattern is found then it must be questioned whether any very strong relationship between prior fixation duration and saccade targeting accuracy exists.

Table 4.11 *Experiments 4 & 5. Mean Landing Position on the Critical Word as a Function of Launch Site and Prior Fixation Duration. Standard Deviations and Number of Data Points Corresponding to Each Mean Shown Respectively in Parentheses. Correlation Coefficient for the Relationship between Prior Fixation Duration and Landing Position for Each Launch Site Category. Prior Fixation Durations Longer than Two Standard Deviations Above the Mean (> 416ms) Were Excluded From this Analysis.*

Launch site	Prior fixation duration (ms)				
	80-119	120-219	220-319	320-416	*r*
1-2	5.1 (1.7, 15)	5.1 (1.5, 451)	5.4 (1.5, 490)	5.1 (1.6, 112)	0.09
2-4	4.2 (1.7, 19)	4.1 (1.6, 402)	4.3 (1.5, 847)	4.3 (1.5, 214)	0.046
5-6	3.0 (2.6, 11)	2.4 (1.7, 337)	3.2 (1.7, 614)	3.2 (1.8, 153)	0.135
≥7	2.6 (2.4, 28)	2.1 (2.2, 416)	1.8 (1.8, 330)	2.8 (2.3, 75)	0.003

Table 4.11 shows the mean landing position on the critical word as a function of launch site and prior fixation duration. Note that saccades launched from far launch sites land numerically nearer the beginning of the word, an effect found in numerous other studies (Hyönä, 1995; McConkie et al., 1994; McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner et al., 1996). The means do not show reduced overshooting (landing positions nearer the word beginning) for long prior fixation durations launched from near launch sites. If the means for short prior fixation durations are disregarded (due to the small number of data points), similar to McConkie et al. (1988), it seems that undershooting is reduced (landing positions are nearer the word centre) for long prior fixation durations launched from distant launch sites. However, it must be stressed that fewer data points contribute to the means for long prior fixation durations. Table 4.11 also shows the correlation coefficients for the relationship between landing position and prior fixation duration for each launch site category. McConkie et al.'s (1988) findings would predict a negative correlation for saccades launched from near launch sites. That is, short prior fixation durations would produce fixation positions further into the word and long prior fixation durations would produce fixation positions nearer the word centre, therefore long prior fixation

durations would reduce overshooting from near launch sites. McConkie et al's findings predict a positive correlation for saccades launched from distant launch sites. That is, short prior fixation durations would produce fixation positions nearer the word beginning and long prior fixation durations would produce fixation positions nearer the word centre, therefore long prior fixation durations would reduce undershooting from distant launch sites. However in the present study, none of the correlations are negative and all are very weak. The results therefore provide no clear evidence in support of McConkie et al's results.

The analyses provide little support for the notion that saccades are targeted more accurately following longer fixation durations. There was no evidence at all for reduced overshooting for saccades launched from near launch sites. Although there were positive correlations (consistent with reduced undershooting) between prior fixation durations and landing position for saccades launched from distant launch sites, these effects were very small. The absence of a relationship between prior fixation duration and subsequent saccade targeting accuracy shown in these single sentence reading results support similar findings reported by Radach and Heller (2000) from a corpus reading study.

4.4.3: Prior fixation duration and subsequent saccade length

The third issue is related to the second in that it is also concerned with the relationship between prior fixation durations and subsequent saccades. Previous studies based on corpora of eye movement reading data have found no relationship between fixation durations and subsequent saccade lengths (Andriessen & de Voogd, 1973; Kliegl et al., 1983; McConkie & Zola, 1984; Radach & Heller, 2000; Rayner & McConkie, 1976). However in an analysis of progressive, first pass interword saccades, Inhoff et al. (1992) found that longer prior fixation durations produced longer subsequent saccades. In order to test if there is a relationship between fixation durations and subsequent saccade lengths in the present experiment, the effect of prior fixation duration on first pass saccades into the critical word were examined.

Only first pass saccades that were launched from word n-1 were included in this analysis to avoid any confound with inflated fixation durations prior to word skipping (Pollatsek et al., 1986). Median splits were applied to prior fixation durations for saccades launched from word n-1 to the critical word. Separate splits were used for each participant and each sentence frame for orthographically regular and irregular critical words to produce a set of short (Participants: $M = 211$; Items: $M = 204$) and long (Participants: $M = 305$; Items: $M = 312$) prior fixation durations. Mean saccade lengths from word n-1 to the critical word were significantly shorter when the prior fixation duration was short (Participants: $M = 7.5$; Items: $M = 7.5$) compared to when it was long (Participants: $M = 7.9$; Items: $M = 7.9$), (F's > 21.9, $ps < .01$), with no interaction between prior fixation duration and orthography (F's < 1). However, when the launch sites of the saccades from word n-1 were analysed as a function of prior fixation duration it was found that launch sites were nearer the critical word when the prior fixation duration was short (Participants: $M = 3.5$; Items: $M = 3.5$) compared to when it was long (Participants: $M = 3.8$; Items: $M = 3.8$), (F's > 5.4, $ps \leq .05$). It is likely that a number of factors may have contributed to the relationship between launch site and fixation duration. One such factor is an effect of fixation location on fixation duration, as described in Section 4.4.2 above. Therefore, although saccade lengths into the critical word were shorter following short prior fixation durations, this is likely to be at least partly due to the finding that prior fixations with short durations were launched from nearer launch sites. That is, saccades following short fixation durations would have to be shorter in order to aim for the centre of the following word.

Although initial analyses indicated a relationship between prior fixation durations and saccade lengths, effects of launch site confounded this effect. It is possible that Inhoff et al.'s (1992) results might also be, at least partly, explained by differences in launch site. The results demonstrate the extent to which many factors in this area are non-independent. Consequently, analyses such as the relationship between fixation durations and subsequent saccade lengths should be treated with caution.

4.4.4: Discussion

The additional analyses of Experiments 4 and 5 provide further insight into the nature of basic processes during eye movements in reading. The finding of an inverted optimal viewing position for both five and six letter and nine and ten letter words challenges Reichle et al.'s (in press) model of eye movements in reading, and perhaps other accounts (Engbert et al., 2002; Reilly & Radach, 2003; Yang & McConkie, 2001) that suggest that fixation durations should be shorter at word central fixation positions due to acuity limitations.

Reichle et al. also predict reduced overshooting for saccades launched from near launch sites and reduced undershooting for saccades launched from far launch sites for long prior fixation durations compared to short prior fixation durations. However although the additional analyses showed some very weak evidence for reduced undershooting for saccades launched from distant launch sites there was no evidence for reduced overshooting. Further evidence (from larger data sets) is clearly needed to undertake a proper test of whether saccade targeting accuracy is influenced by prior fixation durations. However the present results at least suggest that such a relationship, if it exists, is not very strong. In addition, the analyses urge caution when interpreting effects of prior fixation duration on subsequent saccade lengths when other factors such as launch site are not controlled.

4.5: Conclusions

Experiments 4 and 5 show that, for near launch sites, the eyes land nearer to the beginning of words with orthographically irregular than regular initial letter sequences. Experiment 5 shows that these results hold for both lower and upper case text. The results indicate that orthographic regularity influences where words are first fixated even with visually less distinctive text. Both experiments also show that characteristics of words, at least at the level of orthography, influence the direction and length of within word saccades. Note that the effects of orthography on landing positions in Experiments 4 and 5 are only reliable for saccades launched from near launch sites (the previous word). In contrast, Radach et al. (in press) showed that the effects of orthography held for saccades launched from both near and far launch sites. Nevertheless, it does seem that there must be some reduction in the size of the effects at distant launch sites due to reduced acuity for more eccentric targets.

Current models of eye movements in reading do not attempt to explain such influences of orthography on initial or refixation positions (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990).

The fact that the effects hold for upper case text suggests that the effects might not be dependent on processing of low spatial frequency features (Reichle et al., in press) and may be mediated by abstract rather than visual (Findlay & Walker, 1999) processing of orthographic familiarity. As explained in Sections 4.1.3 and 4.3.3, the influence of orthography on saccade lengths into the critical words is consistent with both attraction (Beauvillain et al., 1996; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) and general linguistic processing (Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992) based explanations of landing position effects. Chapter 5 will detail experiments that specifically aim to test these alternative explanations.

Neither Experiment 4 nor 5 showed any evidence of parafoveal-on-foveal effects on either prior fixation durations or probabilities. The fact that all of the five experiments presented so far in this thesis show no evidence of parafoveal-on-foveal effects on fixation durations, and no consistent evidence for parafoveal-on-foveal effects on fixation probabilities, seriously questions the existence, or at least the robustness, of these effects in normal reading. The absence of parafoveal-on-foveal effects is inconsistent with parallel processing accounts (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Schiepers, 1980) but consistent with serial processing accounts (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press) of eye movements in reading.

Further analyses of the effects of case in Experiment 5 indicate that there is very little difference in eye movement measures between lower and upper case text. The similarity between these conditions suggests that very similar processes, such as abstract preprocessing of non-foveal text, might be involved in reading these two types of text. Additional analyses of Experiments 4 and 5 suggest that fixation durations are longer at the word centre than towards the beginning and ends of words (an inverted optimal viewing position). Furthermore, the data provide no evidence to suggest a relationship between prior fixation duration and saccade targeting accuracy or subsequent saccade lengths.

Chapter 5

Testing the Processing Difficulty Hypothesis

Experiment 1 (Chapter 2) and Experiments 4 and 5 (Chapter 4) show that the orthographic characteristics of non-foveal words can be preprocessed and influence saccade programming. The Experiments show that saccades land nearer to the beginning of orthographically irregular than regular beginning words. As explained in Section 1.3.4, current models of eye movements in reading do not attempt to explain these results (O'Regan, 1990; Reichle et al. 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990). Reichle et al. (in press) suggested that low spatial frequency processing of features such as ascenders and descenders might influence saccade computation. However Experiment 5 showed that orthography influences fixation positions even for visually less distinctive upper case text. It seems doubtful that low spatial frequency processing might explain influences of orthography on fixation positions for upper case text. Consequently it does not seem likely that Reichle et al.'s suggestion might entirely explain the influence of orthography on fixation positions. Furthermore, Findlay and Walker (1999) suggested that the visual familiarity (intrinsic salience) of letter sequences might influence saccade computation. However, the fact that Experiment 5 shows that the effects hold for both lower and upper case text is at least suggestive of the possibility that the effects might be determined by abstract rather than visual processing of familiarity.

As detailed in Section 1.3.3, a number of alternative accounts have been proposed to explain the influence of orthography on fixation positions. These accounts can generally be categorised as attraction (Beauvillain et al., 1996; Hyönä, 1993b; McConkie, 1979; Underwood et al., 1990) or general linguistic processing (Hyönä & Pollatsek, 1998, 2000; Radach et al., in press; Rayner & Morris, 1992) explanations. The general linguistic processing accounts are generally based on the notion that the same processes that determine word skipping also influence where words are first fixated. As described in Section 1.3.3, Radach et al. and Rayner and Morris have made suggestions in line with this approach. However Hyönä and Pollatsek have proposed a more fully specified version of a general linguistic processing account which they refer to as the processing difficulty hypothesis. This Chapter will focus on testing the processing difficulty hypothesis, though the results also have implications for other general linguistic processing accounts.

Hyönä and Pollatsek's (1998, 2000) processing difficulty hypothesis is based on two fundamental assumptions. First, foveal (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999) and non-foveal (Balota et al., 1985; Inhoff & Rayner, 1986) processing load both limit non-foveal processing (see Section 1.1.2). Secondly, the extent of non-foveal processing influences the length of subsequent saccades (O'Regan, 1990; Rayner & Morris, 1992; Rayner et al., 1996) (see Section 1.3.3). On the basis of these assumptions Hyönä and Pollatsek (2000) formulated their processing difficulty hypothesis:

> According to the hypothesis, the perceptual span around the fixation from which useful information is picked up is narrowed down with increasing difficulty in parafoveal and foveal processing. Thus, when a word in foveal or parafoveal vision is low-frequency, less parafoveal processing will be done, which should then lead to a shorter forward saccade. p.77.

As explained in Section 1.3.3, Hyönä and Pollatsek (2000) suggest that a weak version of the hypothesis simply predicts that foveal and non-foveal processing difficulty influence refixation and skipping probabilities. However, a strong version of the hypothesis predicts that foveal and non-foveal processing difficulty also influence where exactly words are fixated. Hyönä and Pollatsek specifically refer to the perceptual span changing in size depending on processing load. However it should be noted that it is possible that processing difficulty might limit the type, rather than the extent, of non-foveal processing. For example, foveal processing difficulty might limit linguistic, but not visual, processing of word n+1. Nevertheless, Hyönä and Pollatsek's explanation of saccades depending on the extent of processing requires a clear cut "span" of processing in order to simply formulate the hypothesis.

Furthermore, Hyönä and Pollatsek's hypothesis explains differences in landing positions entirely by differences in saccade lengths, whereas the attraction explanations might also predict differences in launch sites. Experiment 1 (Section 2.2.3), Experiment 4 (Section 4.1.3) and Experiment 5 (Section 4.2.3) all showed consistent (but often non-significant) effects of saccade length such that saccades were shorter into orthographically irregular than regular beginning words. However the mean differences in landing position are rarely accompanied by the same mean numerical differences in saccade length, which suggests that differences in launch site are also contributing to the landing position effect (see Section 1.3.1). For example, as explained in Section 1.3.3, saccades might be attracted from distant launch sites such that the probability of skipping word n-1 is increased and the probability of refixating word n-1 is reduced when the critical string is orthographically irregular compared to when it is regular. Note that such effects would also be indicative of parafoveal-on-foveal effects, as explained in Section 1.5. Nevertheless, there are no consistent differences in fixation probabilities prior to fixating the critical word and therefore there are no clear explanations of how differences in launch site might arise. Therefore it is difficult to criticise extent of processing explanations for not accounting for differences in launch site when the basis of any launch site differences are so unclear. As explained in Section 1.3.3, another aspect of the hypothesis that is testable is the relationship between foveal and non-foveal processing difficulty.

Following Sternberg's (1969) additive factors logic, Hyönä and Pollatsek's (2000) account predicts that the effects of foveal and non-foveal processing difficulty should interact if they impact on the same cognitive processor. That is, when foveal processing difficulty is low, non-foveal preprocessing, and therefore saccade lengths, will be limited by non-foveal processing difficulty. However, when foveal processing difficulty is high, non-foveal preprocessing will be reduced and so there will be no, or reduced, effects of non-foveal processing difficulty on saccade lengths. Note that this prediction is based on an interpretation of Hyönä and Pollatsek's account in which foveal and non-foveal difficulty impact on the same processing resources and in which there is preferential or serial processing of the foveal word over the non-foveal word.

Other explanations of landing position effects which are based on general linguistic processing guiding saccades might also predict an interaction between foveal and non-foveal processing difficulty. As explained in Section 1.3.3, Rayner and Morris (1992) suggest that if skipping processes operate within words then orthographically regular letter sequences might be more likely to be skipped than orthographically irregular letter sequences. It seems likely that such a skipping mechanism would be linked to general sentence processing difficulty rather than just saccade programming to the following word (e.g. Reichle et al., 1998). For example, saccade lengths are shorter for more difficult text (Inhoff et al., 1989; Rayner, 1986), presumably because skipping rates are reduced. In addition, Radach et al. (in press) suggested that Reilly and Radach's (in press) Glenmore model might be adapted such that the linguistic processes that influence the activation of words within a salience map, also influence the activation of letters within the salience map. Hence, the point of maximum salience within the salience map, which determines the saccade target, is influenced by linguistic characteristics within words. As a result of limited processing resources, linguistic influences on saccade targeting might be reduced when foveal processing load is high. Therefore, similar to Hyönä and Pollatsek (2000), both Rayner and Morris and Radach et al. might predict that the effect of orthography on fixation positions is reduced with high foveal load.

Experiments 6 and 7 tested three predictions of the general linguistic processing explanations of the influence of orthography on fixation positions. Two of these predictions are primarily tests of Hyönä and Pollatsek's (2000) processing difficulty hypothesis. First, whether foveal processing difficulty acts to shorten saccades into the following word. Secondly, whether non-foveal processing difficulty acts to shorten saccades into the following word. The third prediction tests a common prediction of the general linguistic processing accounts. That is, whether the effects of foveal and non-foveal processing difficulty interact, such that the effect of non-foveal processing difficulty is smaller in the presence of foveal processing difficulty. In Experiments 6 and 7, foveal processing difficulty is manipulated by word frequency, whereby word n-1 is either frequent, *famous*, or infrequent, *nimble*, in phrases such as *famous performer stood* or *nimble performer stood.* Non-foveal processing difficulty is manipulated by spelling the critical string either correctly, *performer*, or incorrectly, *pwrformer*.

The first prediction testing Hyönä and Pollatsek's (2000) account is that foveal processing difficulty will reduce non-foveal processing and consequently produce shorter saccades into the following word. As explained in Section 1.4, and shown in Experiments 4 and 5 (Chapter 4), the linguistic characteristics of words can influence the length of refixation saccades. These results might be explained by the processing difficulty hypothesis. That is to say, foveal processing difficulty reduces non-foveal processing and so shortens saccades. However, the evidence for foveal processing difficulty shortening saccades out of words is mixed. Liversedge and Underwood (1998) reported that landing positions on a word after a category word tended to be nearer the word beginning when the preceding category word was associated with an atypical compared to a typical instance. However, the modulation of foveal processing difficulty (typicality) was not reflected in reading time measures and a later study found no effect of typicality on landing positions (Rayner et al., 2000). Some studies have found no effect of word frequency on the length of the saccade to the following word (Kennison & Clifton, 1995; Rayner et al., 2000) whereas a recent experiment by Rayner, Ashby, Pollatsek, and Reichle (2003) showed that saccade lengths were 0.5 characters longer out of high frequency than low frequency words. Other studies have shown that foveal processing difficulty in the form of clause wrap up can lengthen subsequent saccades rather than shortening them (Hill & Murray, 2000; Rayner, 1975; Rayner et al., 2000). Therefore, although there is evidence for foveal processing difficulty modulating the length of refixation saccades, there is currently no clear evidence to suggest that foveal processing difficulty shortens saccade lengths to the following word. In Experiments 6 and 7, the processing difficulty hypothesis predicts that high foveal processing load (infrequent word n-1) should reduce non-foveal processing and so produce shorter saccades to the critical string compared to saccades following low foveal processing load (frequent word n-1).

The second prediction of Hyönä and Pollatsek's (2000) account is that non-foveal processing difficulty will reduce non-foveal processing and consequently produce shorter saccades into the following word. Experiments 1, 4 and 5, and other studies suggesting that orthographic (Hyönä, 1995; Radach et al., 2003; Vonk et al., 2000) and morphological (Hyönä & Pollatsek, 1998) non-foveal features can influence fixation positions, might all support the hypothesis that non-foveal processing difficulty can reduce non-foveal processing and influence saccade programming. However, as explained above, not all studies that have shown effects of non-foveal difficulty on fixation locations have shown corresponding effects of saccade length. In Experiments 6 and 7, the processing difficulty hypothesis predicts that high non-foveal processing load (misspelled critical string) should reduce non-foveal processing and so produce shorter saccades to the critical string compared to saccades following low non-foveal processing load (correctly spelled critical string). Note that the other general linguistic processing and attraction accounts might also predict that non-foveal processing difficulty shortens saccade lengths.

The third prediction testing the general linguistic processing accounts is that the effects of foveal and non-foveal processing difficulty should interact. As described in Section 1.3.3, Liversedge and Underwood (1998) attempted to investigate this issue but it is difficult to form meaningful conclusions on the basis of their study because foveal processing difficulty did not influence foveal reading times and non-foveal processing difficulty did not influence fixation positions. In the current study, when the foveal word is difficulty to process (infrequent word n-1), non-foveal processing of the critical string should be limited and so any effects of non-foveal difficulty (spelling of the critical string) should be eliminated or reduced.

In contrast to these predictions, the attraction hypotheses predict no effects of foveal processing difficulty on saccade lengths into the following word. In addition, the attraction hypotheses predict that foveal processing difficulty is independent of attraction processes, therefore there should be no interaction between foveal and non-foveal processing difficulty. As stated above, current models of eye movements in reading predict no effects of either foveal or non-foveal difficulty on fixation positions on words (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990).

Experiments 6 (Section 5.1) and 7 (Section 5.2) test the three predictions outlined above. In addition, as for all of the experiments in this thesis, Experiments 6 and 7 test whether the characteristics of the critical string influence prior fixation durations or fixation probabilities (parafoveal-on-foveal effects, see Section 1.5). Similar to Experiments 1, 2 and 3, Experiments 6 and 7 used misspellings in order to create the strongest possible manipulations of orthography. However, the disadvantage of using misspellings is that once participants fixate the misspelled words reading is disrupted because of the processing difficulty induced by the spelling errors. Therefore, Experiment 7 used the same design and similar materials to Experiment 6, but the saccade contingent change methodology (see Figure 1.1 in Section 1.1.2) was employed in order that the misspellings were removed before the critical strings were fixated. As a result of using this methodology a number of supplementary analyses were required for Experiment 7 (Section 5.3). Section 5.4 includes further discussion of the results of the two Experiments.

5.1: Experiment 6

Experiment 6 tests the three predictions described above. Although Hyönä and Pollatsek's (2000) hypothesis focuses on differences in saccade lengths, there are often effects of non-foveal difficulty on fixation positions without entirely matching differences in saccade lengths. Therefore a less stringent test of their hypothesis will involve testing whether each of the predictions also has any effect on landing positions.

5.1.1: Method

Participants. Forty-four native English speakers at the University of Durham were paid to participate in the experiment. The participants all had normal or corrected to normal vision and were naïve in relation to the purpose of the experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Materials and Design. Word frequencies and case-insensitive n-gram frequencies were calculated using the CELEX English word form corpus (Baayen, et al, 1995). There were two variables, foveal and non-foveal processing difficulty, which were manipulated within participants and items. Foveal processing difficulty was determined by the frequency of word n-1, the foveal word was either frequent (e.g. *famous*) or infrequent (e.g. *nimble*). Non-foveal processing difficulty was determined by the spelling of the critical string, the non-foveal word was spelled correctly (e.g. *performer*) or the second letter was misspelled (e.g. *pwrformer*).

Word n-1 was five or six letters long ($M = 5.5$, $SD = 0.5$) and the word lengths were matched within each experimental sentence. The word frequencies in counts per million for word n-1 were significantly lower for low frequency words ($M = 1$, range: 0 – 5, $SD = 1$) than high frequency words ($M = 182$, range: 34 – 970, $SD = 205$), $t\,(47) = 6.108$, $p < .01$. All of the critical strings were nine or ten characters long ($M = 9.3$, $SD = 0.4$) and the mean word frequency in counts per million was 36 (range: 2 – 201, $SD = 44$). Word n+1 was five or six letters long ($M = 5.5$, $SD = 0.5$).

For the critical string, position specific n-gram frequencies were calculated in counts per 17.9 million. The initial trigrams of the misspelled critical string did not occur at the beginning of any word in the English language. The initial type and token bigram frequencies were significantly lower for the misspelled critical strings (type: $M = 3$, $SD = 7$; token: $M = 85$, $SD = 237$) compared to the correctly spelled critical strings (type: $M = 887$, $SD = 616$; token: $M = 215675$, $SD = 285439$), t's > 5, ps < .01.

Each of the forty-eight critical words were preceded by either one of the 48 low or one of the 48 high frequency words. Word n-1 and the critical string were embedded in sentence frames which were otherwise identical for each condition. Each of the sentences was no longer than one line of text (80 characters) and the critical word appeared approximately in the middle of the sentence. The word after the critical word was either five or six letters long with medium to high frequencies. Most of the sentences included context relevant to the critical word at the beginning of the sentence. See Appendix E for a list of experimental sentences and critical words.

Four lists of 78 items were constructed and eleven participants were randomly allocated to each list. Each list included 48 experimental items of which 12 items were from each of the four conditions. The conditions were rotated following a Latin square design. There were 15 misspelled filler items with misspellings in a variety of word lengths and in a variety of positions within the word and the sentence. There were also 15 filler items that were spelled correctly. Therefore half of the 78 items contained a misspelling. Twenty-six of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences. The sentences were presented in a fixed random order with six filler sentences at the beginning.

Procedure. The procedure was the same as for Experiment 1. Participants were instructed that some sentences would contain misspellings but that they should read and understand the sentences to the best of their ability. The entire experiment lasted approximately 30 minutes and participants were given one break.

Analyses. The analyses were the same as in Experiment 1 except that only saccades actually launched from word n-1 (not the space before) were included in the analyses of saccades (landing positions, saccade lengths, launch sites) into the critical word. Such a procedure helped to ensure that fixations launched from word n-1 were involved in processing of word n-1, and therefore provided the strongest possible test of the processing difficulty hypothesis. Seven percent of trials were excluded due to tracker loss or blinks on first pass reading of words n-1 or the critical string and zero reading times on region one.

5.1.2: Results

The results were analysed using the same measures as used in Experiment 1. Repeated measures analyses of variance (ANOVAs) were undertaken for the variables of foveal (frequent, infrequent) and non-foveal (correctly spelled, misspelled) processing difficulty with participants (F_1) and items (F_2) as random variables. The mean error rate on the comprehension questions was seven percent indicating that participants properly read and understood most of the sentences.

Table 5.1 *Experiment 6. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Standard Deviations in Parentheses.*

Experiment 6		Word n-1		Fixation n-1		
Word n-1	Critical string	FF	GD	All	n-1	≤3
Frequent	Correct	266 (79)	286 (102)	258 (78)	267 (78)	258 (78)
	Misspelled	269 (85)	292 (107)	261 (83)	269 (84)	261 (83)
Infrequent	Correct	295 (97)	334 (125)	285 (98)	299 (99)	285 (98)
	Misspelled	295 (96)	339 (142)	283 (100)	297 (97)	283 (100)

Parafoveal-on-foveal effects. Table 5.1 shows the mean reading time measures on word n-1 and mean fixation durations prior to fixating the critical string. There were no effects of the spelling of the critical string on first fixations or gaze durations on word n-1 (F's < 1). There were also no effects of the spelling of the critical string on the duration of the fixation prior to fixating the critical string for all of the data, for saccades launched from word n-1 and for saccades launched from three or less characters from the beginning of the critical string (F's < 1.1). Therefore the word initial letter sequences of the critical string did not influence fixation durations until they were directly fixated.

Table 5.2 *Experiment 6. Mean Fixation Duration After Leaving Word n-1.Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String. Standard Deviations in Parentheses.*

Experiment 6		Fixation after word n-1	Critical string		
Word n-1	Critical string		FF	GD	TT
Frequent	Correct	286 (93)	286 (91)	341 (121)	420 (211)
	Misspelled	332 (142)	339 (143)	482 (247)	667 (397)
Infrequent	Correct	289 (101)	295 (100)	347 (135)	451 (229)
	Misspelled	330 (150)	332 (146)	488 (272)	677 (370)

Reading time measures: *Frequency of word n*-1. Table 5.1 shows the mean reading time measures on word n-1 for each condition. First fixations, F_1 (1, 43) = 40.37, $p < .01$, $MSE = 750$; F_2 (1, 47) = 33.66, $p < .01$, $MSE = 1091$, gaze durations, F_1 (1, 43) = 85.85, $p < .01$, $MSE = 1118$; F_2 (1, 47) = 79.57, $p < .01$, $MSE = 1437$, and total time, F_1 (1, 43) = 80.46, $p < .01$, $MSE = 3744$; F_2 (1, 47) = 35.32, $p < .01$, MSE = 8902, were significantly longer on word n-1 when it was infrequent compared to when it was frequent. Table 5.2 shows the mean reading time measures on the critical string for each condition and the duration of the fixation after leaving word n-1. There were no effects of the frequency of word n-1 on the fixation after leaving word n-1 (F's < 1) or on first fixations (F's < 1), gaze durations (F's < 1) or total time, F_1 (1, 43) = 2.65, $p = .111$, $MSE = 7389$; F_2 (1, 47) = 1.868, $p = .178$, $MSE = 12167$, on the critical string. Therefore reading times were longer on word n-1 if it was infrequent but there were no effects of frequency on subsequent fixations (spillover). These results are consistent with previous studies showing effects of word frequency on reading times localised to the critical word (Henderson & Ferreira, 1990, 1993; Raney & Rayner, 1995). Importantly, the longer reading times on word n-1 when it was infrequent, compared to when it was frequent, show that the manipulation of foveal processing load was effective.

Table 5.3 *Experiment 6. Mean Fixation Duration After Leaving the Critical String. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on Word n+1. Standard Deviations in Parentheses.*

Experiment 6		Fixation after	Word n+1		
Word n-1	Critical string	critical string	FF	GD	TT
Frequent	Correct	258 (76)	267 (80)	280 (89)	325 (153)
	Misspelled	271 (97)	278 (98)	296 (104)	367 (186)
Infrequent	Correct	266 (92)	269 (99)	277 (106)	325 (162)
	Misspelled	281 (109)	279 (108)	303 (134)	364 (196)

Reading time measures: *Spelling of critical string*. Table 5.2 shows the mean reading time measures on the critical string for each condition. First fixations, F_1 (1, 43) = 39.22, $p < .01$, $MSE = 2255$; F_2 (1, 47) = 103.87, $p < .01$, $MSE = 929$, gaze durations, F_1 (1, 43) = 99.71, $p < .01$, $MSE = 8744$; F_2 (1, 47) = 190.11, $p < .01$, $MSE = 4992$, and total time, F_1 (1, 43) = 125.95, $p < .01$, $MSE = 19734$; F_2 (1, 47) = 173.16, $p < .01$, $MSE = 15295$, were significantly longer on the critical string when it was misspelled compared to when it was spelled correctly. Table 5.3 shows the mean reading time measures on word n+1 for each condition and the duration of the fixation after leaving the critical string. The fixation after leaving the critical string was significantly longer when the critical string was misspelled compared to when it was spelled correctly, F_1 (1, 43) = 11.18, $p < .01$, $MSE = 1000$; F_2 (1, 47) = 13.04, $p < .01$, $MSE = 745$. Reading times were also significantly longer on word n+1 if the critical string was misspelled compared to if it was spelled correctly for gaze duration[1], F_1 (1, 42) = 6.85, $p = .01$, $MSE = 2352$; F_2 (1, 47) = 16.57, $p < .01$, $MSE = 1626$, and total time, F_1 (1, 42) = 23.81, $p < .01$, $MSE = 2976$; F_2 (1, 47) = 43.82, $p < .01$, $MSE = 2104$, and there were no reliable effects for first fixations, F_1 (1, 42) = 1.7, $p = .199$, $MSE = 1853$, F_2 (1, 47) = 5.14, $p = .03$, $MSE = 1441$. Therefore reading times were longer on the critical string if it was misspelled. The spelling of the critical string also produced spillover effects with longer subsequent fixations and longer reading times on word n+1 when the critical string was misspelled.

[1] Reading time measures for word n+1 were calculated across 43 participants for the participants analysis because one reader did not produce data (due to skipping or excluded data) for this word in at least one of the conditions.

These results support those of Experiments 1, 2, and 3, and previous studies (Inhoff & Topolski, 1994; Rayner, Pollatsek et al., 1998; Underwood et al., 1988; Zola, 1984), showing longer reading times on misspelled, compared to correctly spelled, words. In addition, the longer reading times on the misspelled compared to the correctly spelled critical strings suggests that the misspelled strings were more difficult to process. Therefore the manipulation of non-foveal processing difficulty was effective.

Reading time measures: *Foveal and Non-foveal Load.* There were no interactions between the frequency of word n-1 and the spelling of the critical string for either reading times on word n-1 or for gaze durations and total time on the critical string (F's < 1). There was also no reliable interaction for first fixations on the critical string, F_1 (1, 43) = 5.1, p = .03, MSE = 521, F_2 (1, 47) = 1.23, p = .274, MSE = 1970. These results support the claim that there were no parafoveal-on-foveal effects of the spelling of the critical string on reading times on word n-1, regardless of the difficulty of word n-1. In addition, the results show that any kind of continued processing of the frequency of word n-1 did not influence the effects of spelling on reading times on the critical string.

Table 5.4 *Experiment 6. Mean Landing Positions, Incoming Saccade Extents and Launch Sites for Saccades Launched from Word n-1. Standard Deviations in Parentheses.*

Experiment 6		Landing position	Saccade extent	Launch site
Word n-1	Critical string			
Frequent	Correct	4.6 (1.8)	7.7 (1.8)	3.2 (1.5)
	Misspelled	4.5 (1.8)	7.7 (1.8)	3.3 (1.5)
Infrequent	Correct	4.5 (1.9)	7.6 (1.7)	3.2 (1.4)
	Misspelled	4.2 (1.8)	7.4 (1.8)	3.3 (1.4)

Fixation positions: *Frequency of word n*-1. Table 5.4 shows the mean landing positions, saccade lengths and launch sites for the critical string for saccades launched from word n-1. Mean first fixation landing positions were significantly nearer the beginning of the critical string (for saccades launched from word n-1) when word n-1 was infrequent (M = 4.3, SD = 1.9) compared to when word n-1 was frequent (M = 4.5, SD = 1.8), F_1 (1, 43) = 4.38, p = .04, MSE = 0.45; F_2 (1, 47) = 6.33, p = .02, MSE = 0.39. Consistent with these results, Figure 5.1 shows that more fixations land at the beginning of the critical string when the previous word is infrequent compared to when it is frequent.

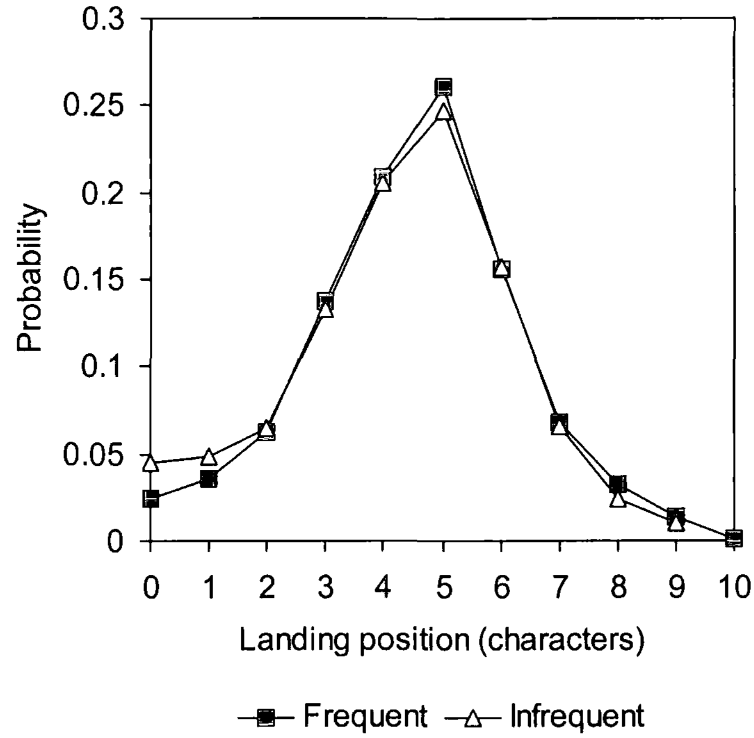

Figure 5.1 Experiment 6. First fixation landing position distributions on the critical string as a function of the frequency of word n-1 for saccades launched from word n-1. Landing position zero is the space before the word and landing position one is the first letter of the word.

Saccades to the critical word were also significantly shorter if word n-1 was infrequent ($M = 7.5$, $SD = 1.7$) compared to when it was frequent ($M = 7.7$, $SD = 1.8$), F_1 (1, 43) = 4.71, $p = .4$, $MSE = 0.39$; F_2 (1, 47) = 8.23, $p < .01$, $MSE = 0.31$. However there was no difference in launch sites prior to fixating the critical word for the frequent ($M = 3.2$, $SD = 1.5$) compared to infrequent ($M = 3.2$, $SD = 1.4$) word n-1 (F's < 1). Figure 5.2 shows the mean landing position on the critical string for each launch site. Consistent with the effects of foveal difficulty on saccade lengths, Figure 5.2 shows that, especially for launch sites near the beginning of word n-1, saccade lengths into the critical string were shorter when word n-1 was infrequent compared to when it was frequent. Therefore, landing positions on and saccade lengths into the critical string were influenced by foveal processing difficulty on the previous word.

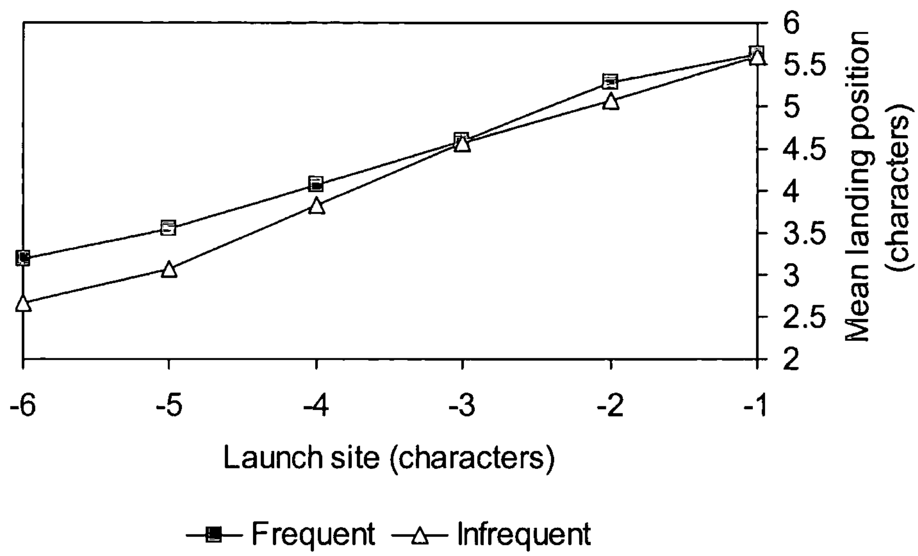

Figure 5.2 Experiment 6. Mean landing position on the critical string for each launch position when word n-1 is frequent or infrequent.

Fixation positions: *Spelling of the critical string*. Across all of the data, mean first fixation landing positions were significantly nearer the beginning of the misspelled critical string ($M = 3.7$, $SD = 2.1$) compared to the correctly spelled critical string ($M = 4.0$, $SD = 2.2$), F_1 (1, 43) = 7.72, $p < .01$, $MSE = 0.36$; F_2 (1, 47) = 7.29, $p = .01$, $MSE = 0.41$. Also, mean saccade lengths into the critical string were numerically shorter when the critical string was misspelled ($M = 8.3$, $SD = 2.6$) compared to when it was spelled correctly ($M = 8.5$, $SD = 2.7$) and this was significant across participants, F_1 (1, 43) = 5.03, $p = .03$, $MSE = 0.48$, but not across items, F_2 (1, 47) = 2.59, $p = .114$, $MSE = 0.73$. There was no difference in mean launch sites prior to fixating the critical string for correctly spelled ($M = 4.5$, $SD = 3$) compared to misspelled ($M = 4.6$, $SD = 3$) critical strings (F's < 1).

Table 5.4 shows the mean landing positions, saccade lengths and launch sites for the critical string for saccades launched from word n-1. Mean first fixation landing positions were significantly nearer the beginning of the misspelled critical string ($M = 4.3$, $SD = 1.8$) compared to the correctly spelled critical string ($M = 4.5$, $SD = 1.9$), F_1 (1, 43) = 4.81, $p = .03$, $MSE = 0.41$; F_2 (1, 47) = 7.2, $p = .01$, $MSE = 0.47$. Figure 5.3 shows that the preferred viewing position curve is shifted to the left when the critical word is misspelled. Also note that Figures 5.1 and 5.3 both show clear preferred viewing positions. For saccades launched from word n-1, most fixations land on the centre or just left of the centre of the word.

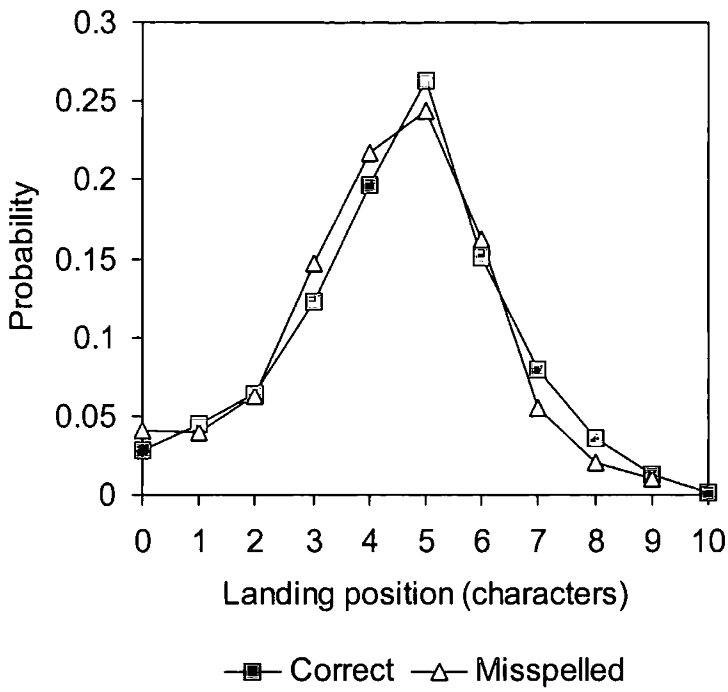

Figure 5.3 Experiment 6. First fixation landing position distributions on the critical string for correctly spelled and misspelled critical strings for saccades launched from word n-1. Landing position zero is the space before the word and landing position one is the first letter of the word.

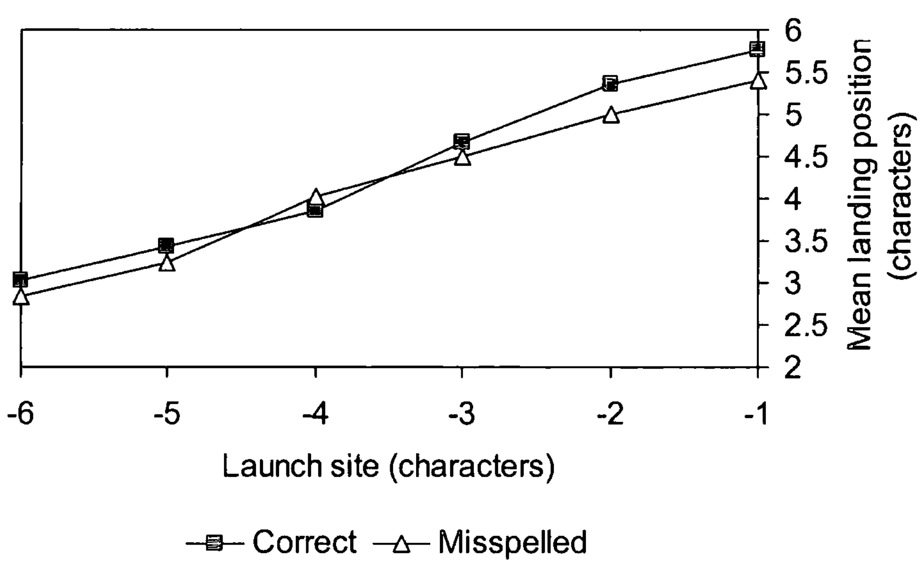

Figure 5.4 Experiment 6. Mean landing position on the critical string for each launch position for correctly spelled and misspelled words.

Mean saccades to the critical word were also numerically shorter if the critical word was misspelled (M = 7.6, SD = 1.8) compared to when it was spelled correctly (M = 7.7, SD = 1.7), although this difference was not significant, F_1 (1, 43) = 2.03, p = .161, MSE = 0.32; F_2 (1, 47) = 3.65, p = .062, MSE = 0.47. There were no differences in mean launch sites prior to fixating the critical string for correctly spelled (M = 3.2, SD = 1.4) compared to misspelled (M = 3.3, SD = 1.5) critical strings, F_1 (1, 43) = 1.66, p = .204, MSE = 0.21; F_2 (1, 47) = 1.06, p = .309, MSE = 0.27. Figure 5.4 shows the mean landing position on the critical string for each launch site. The graph shows that, especially for launch sites near the beginning of the critical string, saccade lengths into the critical string were numerically shorter when the critical string was misspelled compared to when it was spelled correctly. Therefore landing positions were reliably, and saccade lengths were numerically, influenced by non-foveal processing difficulty.

Fixation positions: *Foveal and Non-foveal Load.* The analyses above show that both foveal (frequency of word n-1) and non-foveal (spelling of the critical string) processing difficulty influenced fixation positions on the critical string. There were no significant interactions between the spelling of the critical word and the frequency of word n-1 both for saccade lengths, F_1 (1, 43) = 2.25, p = .141, MSE = 0.29; F_2 (1, 47) = 2.02, p = .162, MSE = 0.36, and landing positions, F_1 (1, 43) = 1.51, p = .226, MSE = 0.35; F_2 (1, 47) = 1.96, p = .168, MSE = 0.51. Figures 5.5 and 5.6 show that the effect of spelling on mean landing positions and saccade lengths was numerically larger when word n-1 was infrequent compared to when it was frequent. Hyönä and Pollatsek's (2000) processing difficulty hypothesis predicts that the effects of non-foveal processing difficulty should be larger when the foveal word is easy to process. Note that there was no such reliable interaction, and in fact, any numerical differences that did occur go in the opposite direction to Hyönä and Pollatsek's prediction.

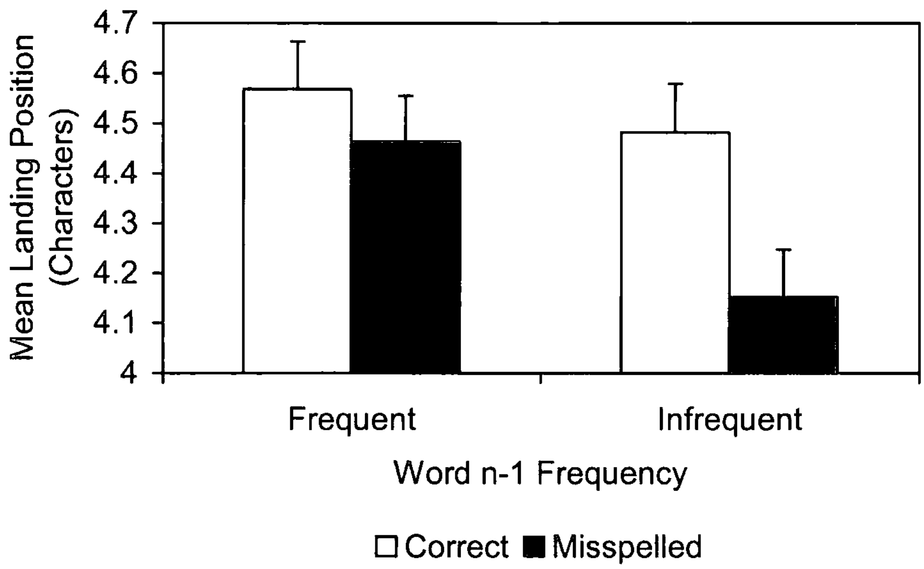

Figure 5.5 Experiment 6. Mean first fixation landing positions on the critical string (+*SE*) for each condition.

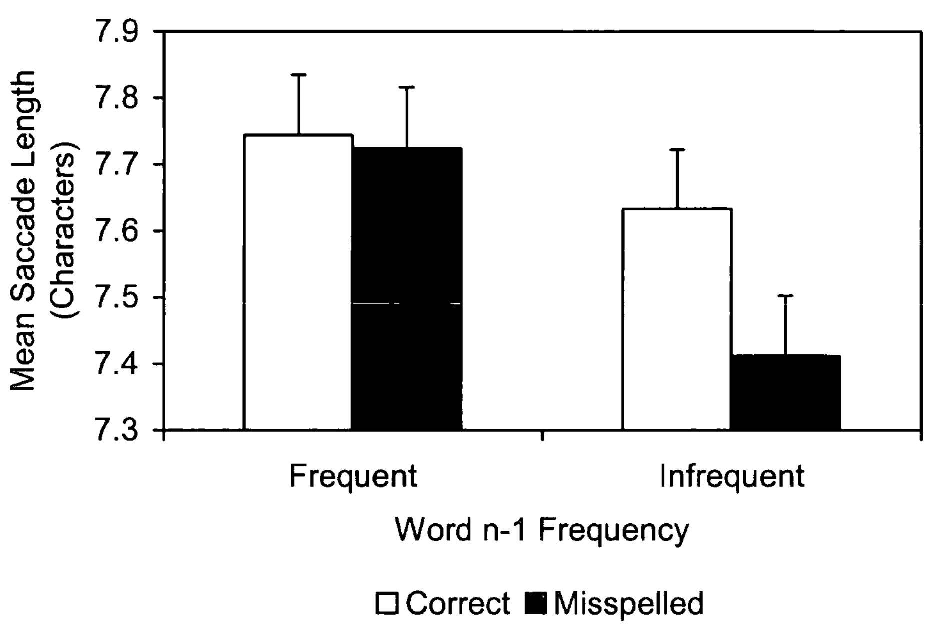

Figure 5.6 Experiment 6. Mean saccade lengths into the critical string (+*SE*) for each condition.

Table 5.5 *Experiment 6. Probability of Skipping and Refixating Word n-1 Directly Before Fixating the Critical String. Probability of Skipping, Making a Single Fixation and Refixating (≥Two) the Critical String on First Pass. Standard Deviations in Parentheses.*

Experiment 6		Word n-1 skip	Word n-1 refixation	Critical string fixation probabilities		
Word n-1	Critical string			Skip	Single	≥Two
Frequent	Correct	0.25 (0.17)	0.02 (0.05)	0.02 (0.04)	0.75 (0.17)	0.23 (0.16)
	Misspelled	0.24 (0.18)	0.05 (0.07)	0.01 (0.03)	0.6 (0.17)	0.39 (0.17)
Infrequent	Correct	0.22 (0.17)	0.08 (0.07)	0.02 (0.04)	0.76 (0.16)	0.22 (0.16)
	Misspelled	0.24 (0.15)	0.1 (0.11)	0.01 (0.04)	0.59 (0.15)	0.4 (0.14)

The previous two sections show that there were no reliable effects of either foveal or non-foveal processing difficulty on the launch site prior to fixating the critical word. Nevertheless, as explained in Section 1.3.3 and 2.2.3, any differences in the probability of skipping or refixating word n-1 might have produced differences in launch site, therefore fixation probabilities for word n-1 were calculated. Table 5.5 shows the probability of skipping and refixating word n-1 directly before fixating the critical string. There were no effects of frequency, spelling and no interaction between frequency and spelling for the probability of skipping word n-1 directly before fixating the critical string (F's < 1). If word n-1 was frequent it was significantly less likely to be refixated directly before fixating the critical string than if it was infrequent, F_1 (1, 43) = 24.38, p < .01, MSE = 54; F_2 (1, 47) = 26.32, p < .01, MSE = 51. If the critical string was misspelled then word n-1 was numerically more likely to be refixated compared to if it was spelled correctly, this was significant across participants, F_1 (1, 43) = 3.97, p = .05, MSE = 49, but not items, F_2 (1, 47) = 3.26, p = .077, MSE = 60. The possibility that this result is an indication of parafoveal-on-foveal effects will be discussed in Section 5.1.3. There was no interaction between the frequency of word n-1 and the spelling of the critical string on the probability of refixating word n-1 directly before fixating the critical string (F's < 1).

The differences in the probability of refixating word n-1 directly before fixating the critical string may have produced differences in launch site which could have influenced initial fixation positions on the critical string. To control for this possibility, the effects were re-calculated for those cases in which a single fixation was made on word n-1 directly before the critical string was fixated. First fixation landing positions were significantly nearer the word beginning when word n-1 was infrequent compared to when it was frequent, F_1 (1, 43) = 7.98, $p < .01$, $MSE = 0.45$; F_2 (1, 47) = 10.88, $p < .01$, $MSE = 0.39$, and when the critical string was misspelled compared to when it was spelled correctly, F_1 (1, 43) = 4.7, $p = .04$, $MSE = 0.42$; F_2 (1, 47) = 4.74, $p = .04$, $MSE = 0.52$, and there was no interaction between foveal and non-foveal processing load on initial fixation positions, F_1 (1, 43) = 1.13, $p = .294$, $MSE = 0.44$; F_2 (1, 47) = 2.26, $p = .139$, $MSE = 0.58$. Saccade lengths were significantly shorter into the critical string when word n-1 was infrequent, F_1 (1, 43) = 10.14, $p < .01$, $MSE = 0.34$; F_2 (1, 47) = 12.3, $p < .01$, $MSE = 0.35$, there were no effects of the spelling of the critical string on saccade lengths into the critical string, F_1 (1, 43) = 1.39, $p = .245$, $MSE = 0.34$; F_2 (1, 47) = 1.78, $p = .189$, $MSE = 0.52$, and there was no interaction between foveal and non-foveal processing load on saccade lengths, $F_1 < 1$; F_2 (1, 47) = 1.98, $p = .166$, $MSE = 0.36$. Therefore the same pattern of results holds for all saccades launched from word n-1 and for those cases in which a single fixation was made on word n-1 directly before the critical string was fixated.

Table 5.6 *Experiment 6. For Cases in Which There Were Multiple First Pass Fixations on the Critical String: Probability of Refixating Word n-1 and the Critical String. Probability of First Refixating to the Left of the Initial Fixation on the Critical String. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 6		Frequent		Infrequent	
		Correct	Misspelled	Correct	Misspelled
Word n-1	Refixation probability	0.09 (0.09)	0.10 (0.09)	0.16 (0.11)	0.15 (0.13)
Critical string	Refixation probability	0.23 (0.16)	0.39 (0.17)	0.23 (0.16)	0.4 (0.15)
	Leftward refixation probability	0.11 (0.23)	0.46 (0.31)	0.19 (0.3)	0.41 (0.33)
	Rightward saccade length	5.5 (1.7)	5.1 (1.8)	5.1 (1.8)	4.9 (1.9)
	Rightward landing position	7.0 (1.5)	6.7 (1.7)	6.8 (1.5)	6.4 (1.9)

Refixations. Table 5.5 shows the probability of skipping, making a single fixation or refixating on the critical string. Table 5.6 shows the probability of refixating on word n-1 and the critical string for those cases in which they were fixated on first pass. Of those trials in which a first pass fixation was made on word n-1, word n-1 was significantly more likely to be refixated when it was infrequent (0.16) compared to when it was frequent (0.1), F_1 (1, 43) = 16.96, $p < .01$, MSE = 101; F_2 (1, 47) = 19.23, $p < .01$, MSE = 91. Of those trials in which a first pass fixation was made on the critical string on first pass, the critical string was significantly more likely to be refixated when it was misspelled (0.4) compared to when it was spelled correctly (0.23), F_1 (1, 43) = 63.24, $p < .01$, MSE = 194; F_2 (1, 47) = 56.83, $p < .01$, MSE = 236. Therefore, both word n-1 and the critical string were more likely to be refixated when they were difficult to process. Similar to the reading time measures, these results confirm that the manipulations of both foveal and non-foveal processing difficulty were effective.

For the critical string, the first refixation was significantly more likely to be to the left of the initial fixation position if it was misspelled (0.43) compared to if it was spelled correctly (0.15), F_1 (1, 37) = 31.36, $p < .01$, MSE = 764; F_2 (1, 41) = 53.44, p

$< .01$, $MSE = 666$. Also for the critical string, initial rightward refixation saccade lengths were numerically smaller for misspelled ($M = 5$) compared to correctly spelled ($M = 5.3$) critical strings, this difference was significant across participants[2], F_1 (1, 30) $= 4.35$, $p = .05$, $MSE = 1.26$, but not across items ($F_2 < 1$). There were no effects of the spelling of the critical string on the landing position of the second first pass fixation, $F_1 < 1$; F_2 (1, 36) $= 1.7$, $p = .201$, $MSE = 1.14$. There were no effects of the frequency of word n-1 on either rightward refixation saccade lengths, F_1 (1, 30) $=$ 2.28, $p = .142$, $MSE = 1.42$; $F_2 < 1$, or rightward refixation landing positions, F_1 (1, 30) $= 1.74$, $p = .198$, $MSE = 1.29$; $F_2 < 1$, and no interactions between frequency and spelling (F's < 1). Therefore the difficulty of the critical string influenced the direction, but not the length or landing position, of refixation saccades. Word n-1 produced insufficient refixation data for such analyses.

5.1.3: Discussion

The reading time and refixation probability results clearly show that the processing difficulty manipulations were effective. That is, word n-1 was more difficult to process when it was infrequent compared to when it was frequent and the critical string was more difficult to process when it was misspelled compared to when it was spelled correctly. There was no evidence of parafoveal-on-foveal effects on fixation durations, that is, the spelling of the critical word did not influence the duration of prior fixations. There were also no significant effects of spelling on fixation probabilities prior to the critical word, however word n-1 tended to be more likely to be refixated if the critical string was misspelled compared to if it was spelled correctly.

The numerically greater probability of refixating word n-1 when the following word is misspelled, might be interpreted as consistent with the results of Kennedy et al. (2002) who showed that word n-1 was more likely to be refixated when the following word was low frequency and informative. However these results must be

[2] The analyses of refixation direction were based on 38 participants and 42 items because six participants and two items did not produce refixations on the critical string in all four of the conditions. The analyses of rightward refixation saccade lengths were based on 31 participants and 37 items because 13 participants and seven items did not produce rightward refixations on the critical string in all four of the conditions.

treated with caution because Kennedy et al. showed quite different results when the following word was high frequency and in the present experiment the frequency of the critical string was uncontrolled. Also note that the greater probability of refixating word n-1 when the critical string is misspelled is in the opposite direction to what might be predicted by attraction hypotheses, as explained in Section 1.3.3. That is, attraction hypotheses may predict that saccades might be attracted from more distant launch sites and so the probability of refixating word n-1 might be reduced. In contrast the (statistically unreliable) results here suggest that word n-1 might be more, not less, likely to be refixated if the following word is misspelled.

As outlined at the beginning of this Chapter, Experiment 6 was primarily undertaken to test two specific predictions of Hyönä & Pollatsek's (2000) hypothesis, and one further prediction of general linguistic processing accounts as a whole. In support of the first prediction based on Hyönä and Pollatsek's account, saccade lengths out of word n-1 were shorter and landing positions were nearer the beginning of the critical string when word n-1 was more difficult to process compared to when it was easy to process. These results are in line with those of Rayner et al. (2003). According to Hyönä & Pollatsek's hypothesis, this result might be explained by reduced preprocessing of the critical non-foveal string. However perhaps an alternative explanation for the results is that when rightward refixations are targeted, some of them will overshoot and land at the very beginning of the following word. Such oculomotor error was more likely to occur on trials in which word n-1 was infrequent than when it was frequent, simply because the infrequent words were more likely to be refixated. Consistent with this suggestion, Figure 5.1 shows that when word n-1 is infrequent compared to when it is frequent, there are more fixations at the very beginning of the critical string, which is where overshooting refixations would be likely to land. In addition, Figure 5.2 suggests that this effect is stronger for saccades launched from nearer the beginning of word n-1, perhaps because this is where many rightward refixations are launched from (Rayner et al., 1996). Perhaps previous studies have shown no effects of word frequency on subsequent saccade lengths (Kennison & Clifton, 1995; Rayner et al., 2000) because they used longer words which may have resulted in fewer cases of refixations overshooting to the following word. Nevertheless, statistically the effects of foveal load on subsequent saccade lengths support the first prediction of Hyönä & Pollatsek's hypothesis.

The results also provide some support for the second prediction of Hyönä & Pollatsek's (2000) hypothesis. Consistent with the results of Experiments 1, 4 and 5, first fixations landed significantly nearer the beginning of the critical string when it was misspelled (orthographically irregular) compared to when it was spelled correctly (orthographically regular). These results are in line with the attraction hypotheses and the other general linguistic processing accounts (Radach et al., in press; Rayner & Morris, 1992). However, the processing difficulty hypothesis would explain this effect entirely by differences in saccade lengths. Although mean differences in saccade lengths could partly explain the difference in landing positions, there were no significant differences in either saccade lengths or launch sites. Also note that, in contrast to Experiment 1, there was no effect of the orthographically irregular misspellings on the probability of skipping the previous word directly before fixating the critical string. For the third prediction derived from Hyönä & Pollatsek's hypothesis and other general linguistic processing accounts, the results showed no evidence of there being a smaller effect of non-foveal processing difficulty when foveal processing load was high. The implications of this result will be discussed further in Section 5.4.

5.2: Experiment 7

In Experiments 1, 2, 3 and 6 participants read sentences that included misspellings. Although the experiments were primarily concerned with preprocessing of the misspellings in non-foveal vision, the misspelled words were subsequently fixated and participants had to work out what the misspelled words should have been in order to understand the sentences. Consequently fixations on the misspelled words, and subsequent fixations, were longer due to the increased processing difficulty induced by the misspellings. As a result, it could be argued that these experiments disrupt reading, or even induce different reading strategies. Despite these possible effects, it is still important that Experiments 1 and 6 show that non-foveal preprocessing of orthography is used to influence saccade programming. Nevertheless, ideally participants would not have to undertake any problem solving to work out what the misspelled words should be. Therefore, the aim of Experiment 7 was to use exactly the same manipulations as Experiment 6 but to use the boundary saccade contingent change technique in order that the misspellings are presented before, but not after, the critical words are fixated. An explanation of this technique is given in Figure 1.1 in Section 1.1.2.

The conditions in Experiment 7 are the same as those in Experiment 6 until the critical string is fixated. Therefore the effects of foveal (word frequency) and non-foveal (spelling) processing difficulty on fixations prior to fixating the critical string, and saccades into the critical string, should be the same in both Experiments. Hyönä & Pollatsek (2000) predict that there should be main effects of foveal and non-foveal difficulty on saccade lengths into and initial landing positions on the critical string. Both Hyönä and Pollatsek and other general linguistic processing accounts (Radach et al., in press; Rayner & Morris, 1992) also predict that there should be an interaction between foveal and non-foveal difficulty such that the effects of non-foveal processing difficulty are smaller when there is high foveal load. In contrast, if the results of Experiment 7 are in line with those of Experiment 6, then there should be main effects of foveal and non-foveal difficulty with no interaction for landing positions on the critical string. Furthermore, reading time measures should be longer on the infrequent compared to frequent word n-1 and there should be no effect of spelling on fixation durations prior to fixating the critical string.

The effects of the spelling of the critical string on reading times on and after the critical string is fixated should be different in Experiment 7 compared to Experiment 6. In Experiment 7, there is a preview (misspelled or correctly spelled) of the critical string but once it is fixated the preview has changed to the correctly spelled string. Experiment 7 therefore provides a measure of the preview benefit derived from correct, compared to misspelled, previews of the critical string. Furthermore, the processing difficulty manipulation of word n-1 enables a test of whether the processing difficulty of the foveal word modulates the amount of preview benefit for the following word, as shown by Henderson and Ferreira (1990) (see Section 1.1.3).

A further interesting issue is that for all the experiments (1, 2, 3 and 6) in which participants fixated misspelled words, initial refixations were found to be more likely to be directed to the left of the initial fixation position for misspelled compared to correctly spelled words. However these experiments can not distinguish between whether non-foveal or foveal processing of the misspelling influenced refixation direction. In Experiment 7 the misspellings are only presented in non-foveal vision. Therefore, if spelling influences refixation direction in Experiment 7 then this must be explained by non-foveal processing of the misspellings. In contrast, if spelling does not influence the direction of refixations in Experiment 7 then this suggests that the effects of spelling on refixation direction when the misspelled words were directly fixated were due to foveal, rather than non-foveal, processing of the misspellings.

To summarise, given the findings of Experiment 6, one might reasonably predict that Experiment 7 should show similar patterns of results for the measures which are sensitive to non-foveal preprocessing of the spelling of the critical string. That is, preprocessing of the spelling of the critical string prior to direct fixation should influence saccade programming to (landing positions on) the critical string, but not fixation durations prior to fixating the critical string. In contrast, measures which are sensitive to foveal processing of the critical string may produce different results. That is, preprocessing of the spelling of the critical string prior to direct fixation might produce preview benefit effects on reading times on the critical string, but these effects are likely to be much smaller than those for foveal effects of spelling on reading times shown in Experiment 6. Therefore the results of Experiment 6 should show effects of spelling which are sensitive to foveal and non-foveal processing and Experiment 7 should show effects of spelling which are only sensitive to non-foveal processing.

5.2.1: Method

Participants. Forty-four native English speakers at the University of Massachusetts in Amherst received course credit or were paid to participate in the experiment. The participants all had normal or corrected to normal vision and were naïve in relation to the purpose of the experiment.

Apparatus. The sentences were presented on a NEC 4FG monitor with the default graphics characters in Borland C++. The monitor was interfaced with a 486 computer through a VGA board. The board was programmed to display 140 lines of pixels so that the refresh rate was 5ms (200Hz). That is, the display changes occurred within 5ms of detection of the boundary having been crossed. The sentences were displayed at a viewing distance of 61cm and 3.8 characters subtended one degree of the visual angle. The room was dimly illuminated. The letters were presented in light cyan (by mixing the green and blue input signals on the monitor) on a black background. The monitor had a P-22 phosphor which allowed blanking of a display to produce a drop to 10% of maximum brightness in 0.06ms.

Eye movements were monitored using a Fourward Technologies Dual Purkinje Generation V eye tracker which was interfaced with the computer. The resolution of the eye tracker is less than 10 min of arc and the sampling rate was every millisecond. Eye movements were recorded from the right eye though viewing was binocular.

Materials and Design. The design was the same as Experiment 6. The materials were largely the same as in Experiment 6 except that some words and phrases had to be changed for American readers. Importantly, the spelling of the critical words' initial letters remained the same. In order to ensure that the frequency manipulation was valid for American college students a familiarity pretest was undertaken. Ten participants rated words on a scale of one (unfamiliar) to seven (familiar). Thirteen words were subsequently excluded due to two or more participants rating these as having a familiarity of one and a further two words were excluded due to concerns that they may be misunderstood by American readers. Consequently, 15 of the infrequent words were replaced with words that fitted into the same sentence frames as the original words. If the replaced infrequent words were a different word length to the original then the high frequency word was also changed to match the new word length.

For the final set of words, the frequent words had significantly higher familiarity ratings ($M = 6.9$, $SD = 0.5$) than the infrequent words ($M = 5.9$, $SD = 1.6$), $t_1(9) = 3.73, p < .01$; $t_2(47) = 11.89, p < .01$. The standard frequency counts were also re-calculated using the American Kuĉera and Francis (1982) corpus. The frequent words had significantly higher frequencies in counts per million ($M = 176$, $SD = 179$) than the infrequent words ($M = 2$, $SD = 3$), $t(47) = 6.72, p < .01$. The mean, minimum and maximum word lengths of word n-1, the critical string and word n+1 were the same as in Experiment 6. Appendix E lists the sentences which were changed for Experiment 7.

Four lists of 98 items were constructed and eleven participants were randomly allocated to each list. Each list included 48 experimental items of which 12 items were from each of the four conditions. The conditions were rotated following a Latin square design. There were 50 filler items for which the words were spelled correctly when directly fixated. Thirty-two of the sentences were followed by a comprehension question to ensure that participants concentrated on understanding the sentences. The sentences were presented in a fixed random order with six filler sentences at the beginning.

Procedure. The procedure was the same as for Experiment 1 except for the following. Bite bars were used to minimize head movements. Participants were instructed to understand the sentences to the best of their ability. Before the presentation of each sentence five boxes appeared extending horizontally from the far left to the far right of the screen in the place of the sentence. Before each sentence was presented the participants looked at each box in turn and a moving box represented the computed eye position. The eye-tracker was re-calibrated if the recordings were inaccurate. If the recordings were accurate the participant looked at the first box (the position of the beginning of the sentence) before the experimenter presented the next trial. The experiment lasted approximately 35 minutes and participants were given two breaks.

The boundary contingent change technique was used such that when the eye crossed an invisible boundary the display changed. For every experimental sentence the invisible boundary was placed at the very end of word n-1. Before the boundary was crossed the critical string was either spelled correctly or misspelled according to the non-foveal processing difficulty condition. After the boundary was crossed the critical string changed to the correctly spelled version, for all of the conditions.

Analyses. The analyses were the same as in Experiment 6 except for the following. For each trial, regardless of the experimental condition, the time at which the display change occurred was compared to the time at which the critical string was first fixated. Trials were excluded if an artefactual "hook" at the end of the saccade crossed the boundary and triggered the display change early, even though the actual fixation occurred to the left of the boundary. In total, 14 percent of trials were excluded due to; display changes happening too early; tracker loss or blinks on first pass reading of words n-1 or the critical string; and zero reading times on region one. Seventeen participants were excluded due to more than twenty-five percent of trials being excluded for any of these reasons.

5.2.2: Results

The results were analysed in the same manner as for Experiment 6. The mean error rate on the comprehension questions was ten percent, indicating that participants properly understood most of the sentences.

Table 5.7 *Experiment 7. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Standard Deviations in Parentheses.*

Experiment 7		Word n-1		Fixation n-1		
Word n-1	Critical string	FF	GD	All	n-1	≤3
Frequent	Correct	271 (85)	303 (127)	266 (89)	275 (92)	273 (94)
	Misspelled	274 (96)	308 (152)	268 (98)	276 (92)	275 (98)
Infrequent	Correct	302 (103)	368 (165)	295 (107)	304 (105)	299 (98)
	Misspelled	305 (116)	363 (162)	297 (118)	309 (119)	330 (139)

Parafoveal-on-foveal effects. Table 5.7 shows the mean reading time measures on word n-1 and mean fixation durations prior to fixating the critical string. There were no effects of the spelling of the critical string on first fixations or gaze durations on word n-1 (F's < 1.1). Figure 5.7 shows the mean fixation durations prior to fixating the critical string for saccades launched from different launch sites. There were no effects of the spelling of the critical string on the fixation prior to fixating the critical string for all of the data or for saccades launched from word n-1 (F's < 1.1). There were no interactions between foveal and non-foveal processing difficulty for any of these measures (F's < 1). These results show no evidence of parafoveal-on-foveal effects and they are consistent with the results of Experiment 6. However, in contrast to the results for all the other experiments presented in this thesis, for saccades launched from three or less characters from the beginning of the critical string[3] prior fixation durations were significantly longer when the critical string was misspelled (M = 304, SD = 124) compared to when it was spelled correctly (M = 288, SD = 97), F_1

[3] For the analyses of fixation durations launched within three characters prior to the critical word, six participants did not contribute data for at least one of the conditions and so the F_1 analysis was based on data from 38 participants.

(1, 37) = 4.53, p = .04, MSE = 1897; F_2 (1, 43) = 5.73, p = .02, MSE = 3634, and there was no interaction between spelling and foveal processing difficulty, F_1 (1, 37) = 2.94, p = .095, MSE = 1559; F_2 (1, 43) = 1.87, p = .179, MSE = 3972. Therefore the spelling of the non-foveal critical string did not influence fixation durations for saccades launched more than three characters from the critical string but spelling (non-foveal difficulty) did influence prior fixations for very near launch sites.

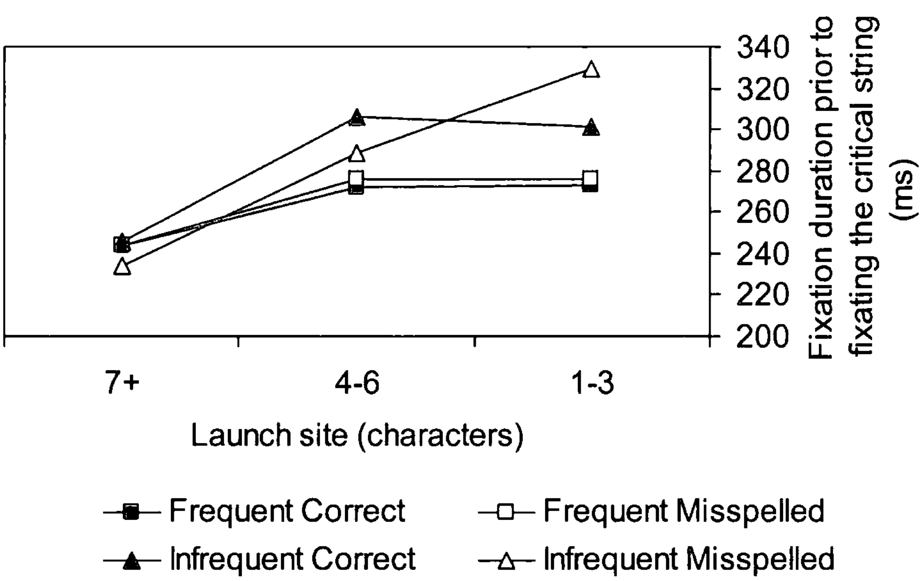

Figure 5.7 Experiment 7. Mean Fixation Duration Prior to Fixating the Critical String for Saccades Launched From Different Launch Site Regions.

Reading time measures: *Frequency of word n*-1. Table 5.7 shows the mean reading time measures on word n-1 for each condition. First fixations, F_1 (1, 43) = 40.15, p < .01, MSE = 1073; F_2 (1, 47) = 32.61, p < .01, MSE = 1455, gaze durations, F_1 (1, 43) = 74.35, p < .01, MSE = 2107; F_2 (1, 47) = 41.87, p < .01, MSE = 4229 and total time, F_1 (1, 43) = 89.47, p < .01, MSE = 6500; F_2 (1, 47) = 49.49, p < .01, MSE = 13387, were significantly longer on word n-1 when it was infrequent compared to when it was frequent.

Table 5.8 *Experiment 7. Mean Fixation Duration After Leaving Word n-1.Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String. Standard Deviations in Parentheses.*

Experiment 7		Fixation after word n-1	Critical string		
Word n-1	Critical string		FF	GD	TT
Frequent	Correct	293 (98)	300 (94)	365 (156)	434 (243)
	Misspelled	303 (110)	304 (102)	385 (150)	451 (213)
	Preview benefit	-	4	20	17
Infrequent	Correct	310 (124)	315 (120)	399 (179)	482 (246)
	Misspelled	327 (131)	332 (126)	418 (179)	504 (262)
	Preview benefit	-	17	19	22

Table 5.8 shows the mean reading time measures on the critical string for each condition and the duration of the fixation after leaving word n-1. The fixation duration after leaving word n-1 was longer when word n-1 was infrequent compared to when it was frequent, F_1 (1, 43) = 11.64, $p < .01$, MSE = 1646; F_2 (1, 47) = 15.76, $p < .01$, MSE = 1339. First fixations, F_1 (1, 43) = 13.53, $p < .01$, MSE = 1547; F_2 (1, 47) = 20.4, $p < .01$, MSE = 1193, gaze durations, F_1 (1, 43) = 14.05, $p < .01$, MSE = 3766; F_2 (1, 47) = 14.11, $p < .01$, MSE = 3650 and total time, F_1 (1, 43) = 11.56, $p < .01$, MSE = 10013; F_2 (1, 47) = 15.01, $p < .01$, MSE = 8289, were also longer on the critical string when word n-1 was infrequent compared to when it was frequent. Therefore reading times were longer on word n-1, the fixation after leaving word n-1 and reading times on the critical string, if word n-1 was infrequent compared to when it was frequent. Therefore there were clear effects of the frequency of word n-1 on both reading times on word n-1 and for measures of spillover. These results support previous studies showing effects of word frequency on reading time measures both on the critical word and the following word (Kennison & Clifton, 1995; Rayner & Duffy, 1986). The results also confirm that the manipulation of foveal processing difficulty was effective.

Reading time measures: *Spelling of the critical string preview*. Table 5.8 shows the mean reading time measures on the critical string and the mean preview benefit when word n-1 was frequent or infrequent for each reading time measure. First fixations were marginally longer when the preview of the critical string was misspelled compared to when it was spelled correctly, this was significant across participants, F_1 (1, 43) = 4.17, p = .05, MSE = 1245, but not items F_2 (1, 47) = 3.69, p = .06, MSE = 1370. However gaze durations were significantly longer when the preview of the critical string was misspelled compared to when it was spelled correctly, F_1 (1, 43) = 6.53, p = .01, MSE = 3269; F_2 (1, 47) = 5.67, p = .02, MSE = 2828. There were no effects of spelling preview on total time, F_1 (1, 43) = 3.38, p = .07, MSE = 4633; F_2 (1, 47) = 2.44, p = .125, MSE = 7106.

Table 5.9 *Experiment 7. Mean Fixation Duration After Leaving the Critical String. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on Word n+1. Standard Deviations in Parentheses.*

Experiment 7		Fixation after	Word n+1		
Word n-1	Critical string	critical string	FF	GD	TT
Frequent	Correct	278 (101)	286 (101)	302 (117)	288 (207)
	Misspelled	272 (90)	277 (93)	291 (99)	304 (186)
Infrequent	Correct	286 (104)	283 (98)	301 (121)	284 (188)
	Misspelled	277 (104)	277 (97)	292 (108)	290 (200)

Table 5.9 shows the mean reading time measures on word n+1 for each condition and the duration of the fixation after leaving the critical string. In contrast to Experiment 6 there was no evidence of spillover of the spelling of the critical string preview on the fixation duration after leaving the critical string, F_1 (1, 43) = 2.76, p = .104, MSE = 844; F_2 (1, 47) = 1.49, p = .228, MSE = 1533, first fixations[4] on word n+1, F_1 (1, 42) = 1.84, p = .182, MSE = 1321; F_2 (1, 47) = 1.38, p = .247, MSE = 1650, gaze durations on word n+1, F_1 (1, 43) = 3.33, p = .075, MSE = 1329; F_2 (1, 47) = 2.41, p = .127, MSE = 2197, or total time on word n+1, $F_1 < 1$; F_2 (1, 47) = 2.02, p = .162, MSE = 3033. The results show that reading times were longer on the critical string when the preview was incorrect (misspelled) compared to when it was correct. There were no spillover effects of preview on subsequent fixation durations.

Reading time measures: *Foveal and non-foveal load.* There were no interactions between the frequency of word n-1 and the spelling of the critical string for reading time measures on word n-1 (F's < 1). According to Henderson and

[4] For the analysis of first fixation durations on word n+1, one participant did not contribute data for at least one of the conditions and so the F_1 analysis was based on data from 43 participants.

Ferreira (1990), foveal processing difficulty reduces non-foveal preview benefit. Therefore Henderson and Ferreira would predict an interaction such that preview benefit for the critical string (correct compared to misspelled preview) should be greater when word n-1 is frequent than when word n-1 is infrequent. However there were no interactions between the frequency of word n-1 and the spelling of the preview of the critical string for first fixations, F_1 (1, 43) = 1.9, p = .175, MSE = 1436; F_2 < 1, gaze durations (F's < 1), or total time (F's < 1) on the critical string. However the likelihood of the difficulty of word n-1 modulating preview benefit of the following word might be reduced for cases in which word n-1 was not fixated, regressions were made out of word n-1 on first pass and for cases in which word n-1 was refixated (refixations might provide a better preview of the following word).

Table 5.10 *Experiment 7. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String for Cases in Which a Single Fixation was Made on Word n-1, and No regressions Were Made Out of Word n-1 on First Pass. Standard Deviations in Parentheses.*

Experiment 7		Critical string		
Word n-1	Critical string	FF	GD	TT
Frequent	Correct	302 (97)	358 (155)	422 (228)
	Misspelled	312 (111)	381 (151)	438 (201)
	Preview benefit	10	23	16
Infrequent	Correct	319 (127)	404 (179)	483 (234)
	Misspelled	343 (130)	420 (160)	505 (226)
	Preview benefit	24	16	22

Table 5.10 shows the mean reading time measures on the critical string when the aforementioned cases were excluded from the analyses[5]. There were significant effects of spelling preview benefit for first fixation durations, F_1 (1, 42) = 5.93, p = .02, MSE = 1618; F_2 (1, 47) = 4.56, p = .04, MSE = 2115, and gaze durations, F_1 (1, 42) = 7.25, p = .01, MSE = 3222; F_2 (1, 47) = 5.71, p = .02, MSE = 3747, and effects across items, F_2 (1, 47) = 3.93, p = .05, MSE = 8212, but not participants, F_1 (1, 42) =

[5] The F_1 analyses of reading time measures on the critical string for cases in which a single fixation was made on word n-1, and no regressions were made out of word n-1 on first pass, are based on data from 43 participants because one participant did not produce data for all four of the conditions.

2.03, $p = .161$, $MSE = 5752$, for total time. Importantly, there were no interactions between foveal load and spelling for any of these measures (F's < 1). Therefore the results clearly show that orthography is preprocessed in non-foveal vision and integrated across saccades such that reading times on the following word are reduced. However, the results show no evidence of foveal processing difficulty limiting non-foveal processing.

Table 5.11 *Experiment 7. Mean Landing Positions, Incoming Saccade Extents and Launch Sites for Saccades Launched from Word n-1. Standard Deviations in Parentheses.*

Experiment 7		Landing position	Saccade extent	Launch site
Word n-1	Critical string			
Frequent	Correct	4.5 (1.7)	8.0 (1.5)	3.5 (1.3)
	Misspelled	4.1 (1.6)	7.7 (1.7)	3.6 (1.3)
Infrequent	Correct	4.3 (1.7)	7.7 (1.7)	3.4 (1.2)
	Misspelled	4.1 (1.6)	7.6 (1.7)	3.5 (1.3)

Fixation positions: *Frequency of word n*-1. Table 5.11 shows the mean landing positions, saccade lengths and launch sites for the critical string for saccades launched from word n-1. For saccades launched from word n-1, there was no difference in landing positions on the critical string when word n-1 was frequent ($M = 4.2$, $SD = 1.6$) compared to when it was infrequent ($M = 4.3$, $SD = 1.7$), F_1 (1, 43) = 3.8, $p = .058$, $MSE = 0.38$; F_2 (1, 47) = 2.27, $p = .138$, $MSE = 0.5$. Consistent with this, Figure 5.8 shows that there is little difference in landing positions on the critical string when word n-1 is frequent compared to when it is infrequent.

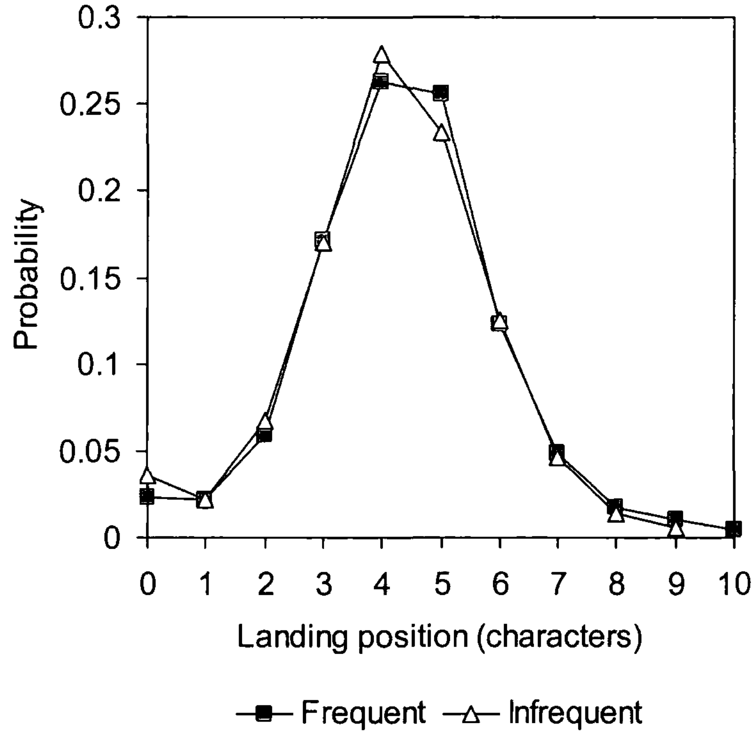

Figure 5.8 Experiment 7. First fixation landing position distributions on the critical string as a function of the frequency of word n-1 for saccades launched from word n-1. Landing position zero is the space before the word and landing position one is the first letter of the word.

Saccades to the critical string from word n-1 were significantly shorter if word n-1 was infrequent ($M = 7.7$, $SD = 1.7$) compared to when it was frequent ($M = 7.9$, $SD = 1.6$), F_1 (1, 43) = 4, $p = .05$, $MSE = 0.44$; F_2 (1, 47) = 3.97, $p = .05$, $MSE = 0.5$. In support of these results, Figure 5.9 shows that saccade lengths into the critical word were numerically longer when word n-1 was frequent compared to when it was infrequent. There was no difference in launch sites prior to fixating the critical word for the frequent ($M = 3.5$, $SD = 1.3$) compared to infrequent ($M = 3.5$, $SD = 1.2$) word n-1 (F's < 1). Therefore, saccade lengths were influenced by foveal processing difficulty.

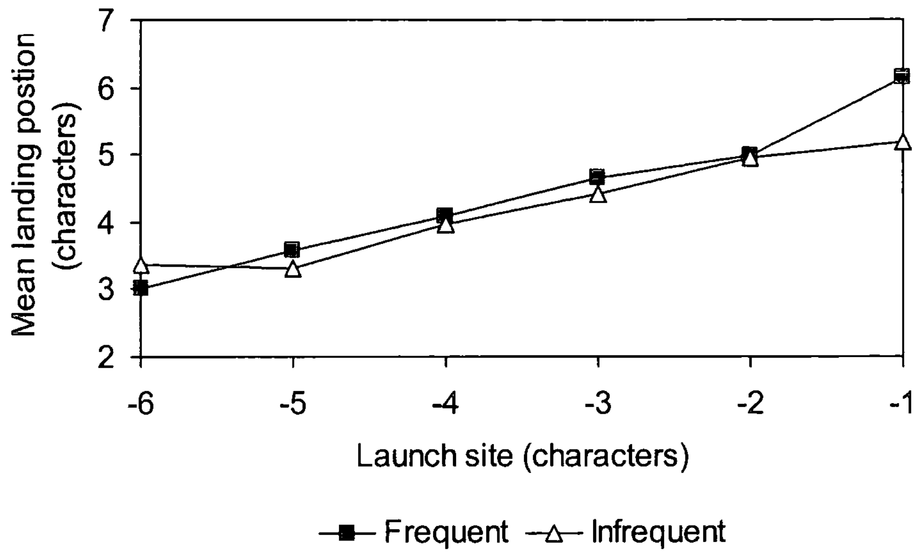

Figure 5.9 Experiment 7. Mean landing position on the critical string for each launch position when word n-1 is frequent or infrequent.

Fixation positions: *Spelling of the critical string.* Across all of the data, mean first fixation landing positions were significantly nearer the beginning of the misspelled critical string ($M = 3.7$, $SD = 1.9$) compared to the correctly spelled critical string ($M = 4.0$, $SD = 2$), F_1 (1, 43) = 13.62, $p < .01$, $MSE = 0.34$; F_2 (1, 47) = 20.3, $p < .01$, $MSE = 0.24$. There were no differences in mean saccade lengths when the critical string was misspelled ($M = 8.4$, $SD = 2.4$) compared to when it was spelled correctly ($M = 8.5$, $SD = 2.3$), $F_1 < 1$; F_2 (1, 47) = 1.65, $p = .205$, $MSE = 0.36$. However mean launch sites prior to fixating the critical string were significantly nearer the critical word for correctly spelled ($M = 4.4$, $SD = 2.4$) compared to misspelled ($M = 4.7$, $SD = 2.5$) critical strings, F_1 (1, 43) = 4.54, $p = .04$, $MSE = 0.55$; F_2 (1, 47) = 4.19, $p = .05$, $MSE = 0.57$.

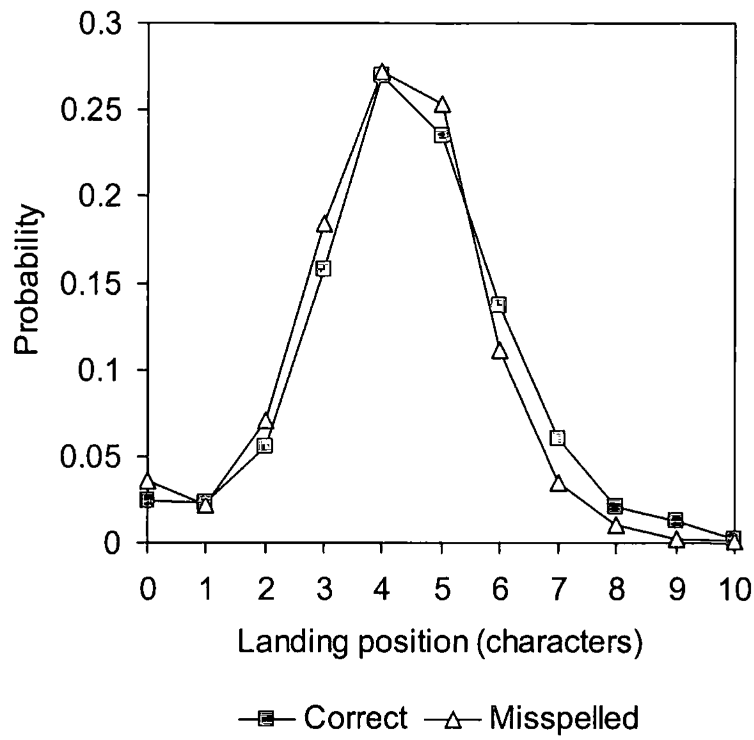

Figure 5.10 Experiment 7. First fixation landing position distributions on the critical string for correctly spelled and misspelled critical string previews for saccades launched from word n-1. Landing position zero is the space before the word and landing position one is the first letter of the word.

Table 5.11 shows the mean landing positions, saccade lengths and launch sites for the critical string for saccades launched from word n-1. Mean first fixation landing positions were significantly nearer the beginning of the misspelled critical string for saccades launched from word n-1 ($M = 4.1$, $SD = 1.6$) compared to the correctly spelled critical string ($M = 4.4$, $SD = 1.7$), F_1 (1, 43) = 13.71, $p < .01$, $MSE = 0.27$; F_2 (1, 47) = 24.89, $p < .01$, $MSE = 0.23$. Consistent with these results, Figure 5.10 shows that the preferred viewing position curve is shifted to the left when the critical word is misspelled compared to when it is spelled correctly. Similar to Experiment 6, Figures 5.8 and 5.10 both show clear preferred viewing positions, for saccades launched from word n-1 most fixations land on the centre or just left of the centre of the word.

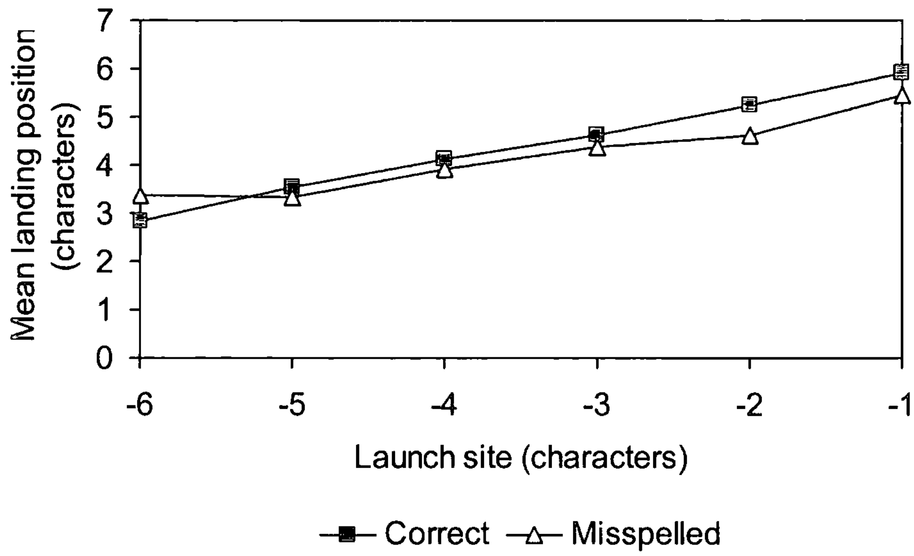

Figure 5.11 Experiment 7. Mean landing position on the critical string for each launch position for correctly spelled and misspelled words.

Mean saccade lengths to the critical word were also numerically shorter if the critical word was misspelled (M = 7.7, SD = 1.7) compared to when it was spelled correctly (M = 7.9, SD = 1.6), although this difference was significant across items, F_2 (1, 47) = 7.14, p = .01, MSE = 0.34, but not participants, F_1 (1, 43) = 2.78, p = .103, MSE = 0.35. In support of these results, Figure 5.11 shows that saccades were numerically shorter into the critical string when it was misspelled compared to when it was correctly spelled for most of the launch sites from word n-1.Mean launch sites prior to fixating the critical string were also numerically nearer the critical string for correctly spelled (M = 3.4, SD = 1.3) compared to misspelled (M = 3.6, SD = 1.3) critical strings and this was significant across participants, F_1 (1, 43) = 5.27, p = .03, MSE = 0.18, but not items, F_2 (1, 47) = 3.58, p = .064, MSE = 0.21. Therefore, misspelled previews of the critical string produced first fixations nearer to the beginning of the critical string compared to when it was spelled correctly. Although there were no reliable effects of either saccade lengths or launch sites it is likely that one or both of these factors contributed to the differences in landing positions.

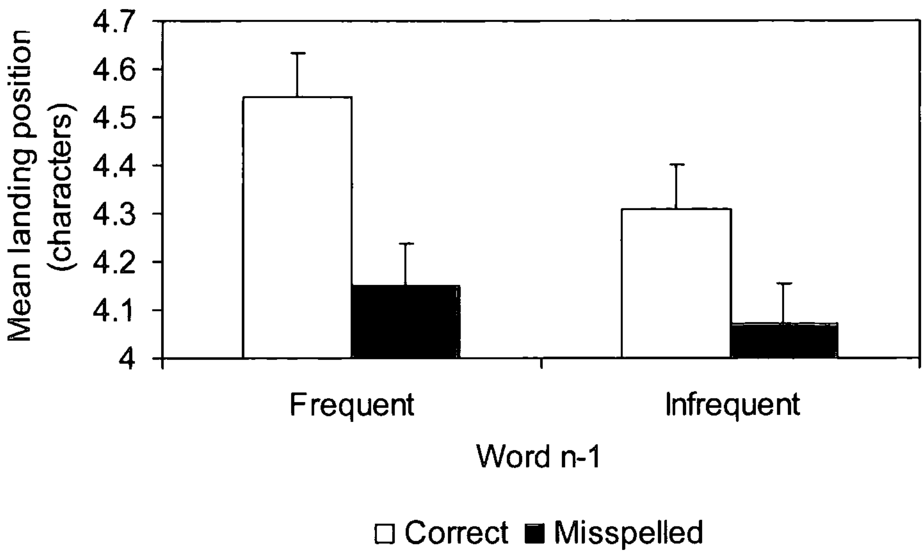

Figure 5.12 Experiment 7. Mean first fixation landing positions (+*SE*) on the critical string for each condition.

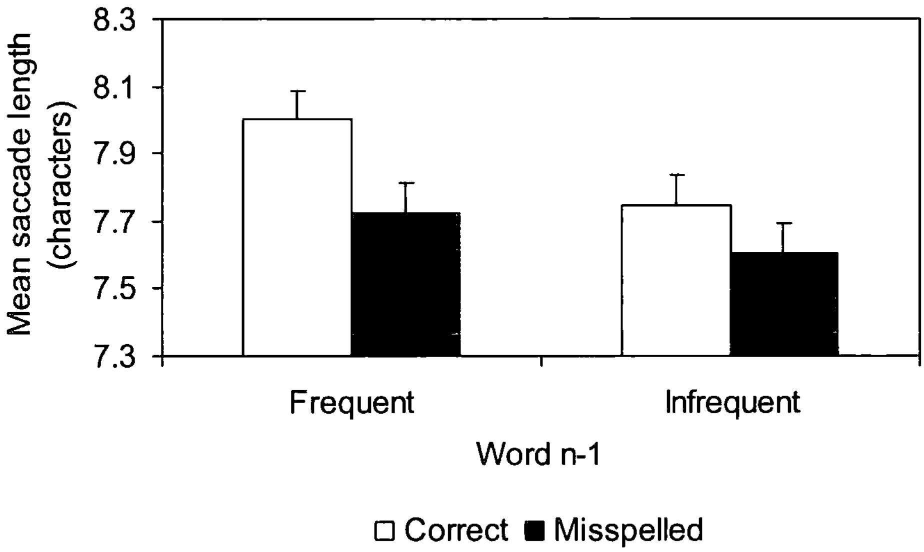

Figure 5.13 Experiment 7. Mean saccade lengths (+*SE*) into the critical string for each condition.

Fixation positions: Foveal and Non-foveal Load. The analyses above show that both foveal (frequency of word n-1) and non-foveal (spelling of the critical string) processing difficulty influenced saccade lengths into or fixation positions on the critical string. Figures 5.12 and 5.13 show the mean landing positions on and saccade lengths into the critical string for each of the conditions. There were no significant interactions between the spelling of the critical word and the frequency of word n-1 for saccades launched from word n-1, for saccade lengths (F's < 1), landing positions, $F_1 < 1$; F_2 (1, 47) = 1.43, p = .238, MSE = 0.31, or launch sites (F's < 1). Therefore both Experiments 6 and 7 show no interaction between foveal and non-foveal processing difficulty.

Table 5.12 *Experiment 7. Probability of Refixating and Skipping Word n-1 Directly Before Fixating the Critical String. Probability of Skipping Word n-1 Directly Before Fixating the Critical String when Trials in Which Regressions Were Made From Word n-1 Were Considered Separately (Skip (exc. regressions)). Probability of Skipping, Making a Single Fixation and Refixating (≥Two) the Critical String on First Pass. Standard Deviations in Parentheses.*

Experiment 7		Word n-1 fixation probabilities			Critical string fixation probabilities		
Word n-1	Critical string	Skip	Skip (exc. regressions)	Refixate	Skip	Single	≥Two
Frequent	Correct	0.24 (0.21)	0.17 (0.15)	0.06 (0.1)	0.01 (0.03)	0.73 (0.18)	0.26 (0.18)
	Misspelled	0.28 (0.23)	0.17 (0.13)	0.06 (0.1)	0.01 (0.02)	0.65 (0.22)	0.34 (0.22)
Infrequent	Correct	0.18 (0.17)	0.11 (0.12)	0.14 (0.18)	0 (0.01)	0.68 (0.2)	0.32 (0.2)
	Misspelled	0.19 (0.2)	0.1 (0.11)	0.14 (0.15)	0 (0)	0.67 (0.23)	0.33 (0.23)

The previous two sections show that there were no reliable effects of either foveal or non-foveal processing difficulty on the launch site prior to fixating the critical word. Nevertheless, as explained in Section 1.3.3, any differences in the probability of skipping or refixating word n-1 might have produced differences in launch site. Therefore, similar to Experiment 6, fixation probabilities for word n-1 were calculated. Table 5.12 shows that word n-1 was significantly more likely to be skipped, F_1 (1, 43) = 17.94, p < .01, MSE = 130; F_2 (1, 47) = 7.94, p < .01, MSE = 339, and significantly less likely to be refixated, F_1 (1, 43) = 21.8, p < .01, MSE = 118; F_2 (1, 47) = 26.82, p < .01, MSE = 107, directly before fixating the critical string when word n-1 was frequent compared to when it was infrequent. However there were no effects of the spelling of the critical string on the probability of skipping word n-1 directly before fixating the critical string, F_1 (1, 43) = 1.41, p = .242, MSE = 149; F_2 (1, 47) = 1.18, p = .284, MSE = 128, or, in contrast to Experiment 1, when those cases in which regressions were made from word n-1 were considered separately (F's < 1). There were also no effects of spelling on the probability of refixating (F's < 1) word n-1 directly before fixating the critical string. There were also no interactions between the frequency of word n-1 and the spelling of the critical string for either of these measures (F's < 1).

Similar to Experiment 6, the effects of the frequency of word n-1 on the probability of refixating word n-1 may have produced differences in launch site which could have influenced initial fixation positions on the critical string. To control for this possibility, the effects were re-calculated for those cases in which a single fixation was made on word n-1 directly before the critical string was fixated. For landing positions on the critical string, there were no significant effects of the frequency of word n-1, F_1 (1, 43) = 3.25, p = .078, MSE = 0.40; F_2 (1, 47) = 3.62, p = .06, MSE = 0.52, significant effects of spelling, F_1 (1, 43) = 14.52, p < .01, MSE = 0.35; F_2 (1, 47) = 21.74, p < .01, MSE = 0.29, and no interaction between the frequency of word n-1 and the spelling of the critical string (F's < 1). For saccade lengths into the critical string there were numerical differences similar to those for all of the data, however there were no reliable effects of the frequency of word n-1, F_1 (1, 43) = 2.32, p = .135, MSE = 0.52; F_2 (1, 47) = 4.89, p = .03, MSE = 0.55, no reliable effects of the spelling of the critical string, F_1 (1, 43) = 3.1, p = .086, MSE = 0.4; F_2 (1, 47) = 5.92, p = .02, MSE = 0.39, and no interactions between the frequency of word n-1 and the spelling of the critical string, F_1 (1, 43) = 1.28, p = .264, MSE = 0.46; F_2 < 1. Therefore the same pattern of landing position and saccade length results hold for all saccades launched from word n-1 and for those cases in which a single fixation was made on word n-1 directly before the critical string was fixated.

Table 5.13 *Experiment 7. Probability of Refixating Word n-1 and the Critical String for Cases in Which These Strings Were Fixated on First Pass. For Cases in Which There Were Multiple First Pass Fixations on the Critical String: Frequency of First Refixating to the Left of the Initial Fixation on the Critical String. Mean Rightward Saccade Lengths and Landing Positions, Standard Deviations in Parentheses.*

Experiment 7		Frequent		Infrequent	
		Correct	Misspelled	Correct	Misspelled
Word n-1	Refixation probability	0.13 (0.15)	0.13 (0.16)	0.22 (0.2)	0.21 (0.19)
Critical string	Refixation probability	0.26 (0.18)	0.35 (0.22)	0.32 (0.2)	0.33 (0.23)
	Leftward refixation probability	0.2 (0.29)	0.18 (0.23)	0.2 (0.38)	0.19 (0.31)
	Rightward saccade length	4.7 (2)	4.6 (1.9)	4.4 (1.8)	4.3 (1.7)
	Rightward landing position	6.9 (1.4)	6.6 (1.6)	6.8 (1.5)	6.8 (1.5)

Refixations. Table 5.12 shows the probability of skipping, making a single fixation and refixating the critical string on first pass. Table 5.13 shows the probability of refixating on word n-1 and the critical string for cases in which they were fixated on first pass. Of those trials in which a first pass fixation was made on word n-1, word n-1 was significantly more likely to be refixated when it was infrequent (0.21) compared to when it was frequent (0.13), F_1 (1, 43) = 33.3, $p < .01$, MSE = 100; F_2 (1, 47) = 20.2, $p < .01$, MSE = 174. Similar to Experiment 6, these results suggest that word n-1 was more difficult to process when it was infrequent compared to when it was frequent. Therefore the manipulation of foveal processing load was clearly effective.

Of those trials in which a first pass fixation was made on the critical string on first pass, the critical string was significantly more likely to be refixated when the preview was misspelled (0.34) compared to when the preview was spelled correctly (0.29), F_1 (1, 43) = 5.27, $p = .03$, MSE = 268; F_2 (1, 47) = 5.19, $p = .03$, MSE = 219. These results correspond to the effects of preview on gaze durations on the critical string. They show that the orthographic characteristics of the critical string were preprocessed and integrated across saccades such that the critical string was less likely to be refixated if the preview was correct compared to if it was incorrect.

For the critical string there was no difference in the probability of refixating to the left for correctly spelled or misspelled previews (F's < 1). There were no effects of the spelling of the critical string preview (F's < 1.1), the frequency of word n-1, F_1 (1, 25) = 3.07, $p = .092$, $MSE = 1.5$; F_2 (1, 34) = 2.72, $p = .108$, $MSE = 1.37$, and no interaction between spelling and frequency (F's < 1), for rightward refixation saccade lengths on the critical string. There were also no effects of spelling, F_1 (1, 25) = 3.06, $p = .093$, $MSE = 0.77$; $F_2 < 1$, frequency (F's < 1) and no interaction between spelling and frequency (F's < 1), for rightward refixation landing positions on the critical string. Therefore processing difficulty on the previous word and the preview of the critical string had no effect on refixation directions, saccade lengths or landing positions on the critical string.

5.2.3: Discussion

The reading time measures show that word n-1 was more difficult to process when it was infrequent compared to when it was frequent. Furthermore, word n-1 was less likely to be refixated and more likely to be skipped when it was frequent compared to when it was infrequent. Therefore the manipulation of foveal processing difficulty was clearly effective.

The results also showed some evidence of parafoveal-on-foveal effects. Fixations launched three or less characters away from the critical string directly before fixating the critical string were significantly longer when the critical string was misspelled compared to when it was spelled correctly. Such results are in line with previous studies that have shown that fixation durations can be influenced by the orthographic characteristics of the following word (Inhoff, Starr, et al., 2000; Rayner, 1975; Underwood et al., 2000; Vitu et al., in press; Starr & Inhoff, in press). However, note that the effect is isolated to fixations at the very end of the previous word. As explained in Section 1.5, such effects could be due to saccades targeted to the critical string which undershot and landed on the previous word. Starr and Inhoff (in press) argued that orthographic parafoveal-on-foveal effects can extend to fixation positions beyond the range of oculomotor error. However the effects in Experiment 7 were isolated to fixations very near the critical string. Therefore the parafoveal-on-foveal effects could either be due to parallel processing of words or oculomotor error. It should also be noted that if such effects were strong and reliable, then they should also have appeared in the other six Experiments presented in this thesis, but this is the only Experiment to show such effects. Furthermore, in this Experiment there were no effects of spelling on fixation probabilities prior to fixating the critical string.

Experiment 6 showed highly significant effects of spelling on all of the reading time measures on the critical string. In contrast, for all of the data, Experiment 7 showed no reliable effects of spelling for first fixation durations and total time on the critical string. These results suggest that the effects of spelling on reading times are larger when the spellings are directly fixated (Experiment 6) compared to when they are only available prior to fixating the word (Experiment 7). Nevertheless, when only trials in which word n-1 was fixated and no regressions were made from word n-1 were included, there were significant preview benefit effects for both first fixations and gaze durations. The effects of preview benefit clearly show that the orthography of the critical string was preprocessed before it was fixated and this information was integrated across saccades such that it facilitated processing of (shortened reading times on) the critical string when it was subsequently fixated. These results support many previous studies showing that non-foveal orthographic information can be preprocessed such that it influences subsequent reading times (see Section 1.1.3). However, the difficulty of word n-1 did not modulate the preview benefit derived from the following word. This result contrasts with that of Henderson and Ferreira (1990). The assumption that foveal difficulty limits non-foveal processing is crucial to Hyönä and Pollatsek's (2000) processing difficulty hypothesis. Therefore it is possible that foveal processing load did not modulate the effects of orthography on saccades into the critical string because foveal processing load simply did not modulate the extent of orthographic non-foveal preprocessing. This issue will be considered further in Section 5.4.

Similar to Experiment 6, saccade lengths were shorter into the critical string when word n-1 was infrequent compared to when it was frequent. However, unlike Experiment 6, the distribution of landing positions (Figure 5.8) and the mean saccade lengths for each launch site (Figure 5.9) were not so suggestive of the possibility that the effects might be due to overshooting refixations aimed for word n-1. Nevertheless, similar to Experiment 6, statistically the results support the first prediction based on

Hyönä and Pollatsek's (2000) hypothesis, that foveal processing difficulty produces shorter saccades to the following word.

Also similar to Experiment 6, first fixation positions landed nearer to the beginning of the critical string when it was misspelled compared to when it was spelled correctly. These results also support the findings in Experiments 1, 4 and 5 showing that orthographic regularity modulates fixation positions on words. Although there were no reliable effects of saccade lengths or launch sites, the numerical differences suggest that both these variables contributed to the effect. Therefore, similar to Experiment 6, the effects of non-foveal difficulty on saccade programming provide some support for the second prediction based on Hyönä and Pollatsek's hypothesis, and support for the other general linguistic processing and attraction accounts. Also note that, as in Experiment 6 and in contrast to Experiment 1, there were no significant effects of spelling on the probability of skipping word n-1. Importantly, similar to Experiment 6 and in contrast to the third prediction based on general linguistic processing accounts (Hyönä & Pollatsek, 2000; Radach et al., in press; Rayner & Morris, 1992), there was no evidence of an interaction between the frequency of word n-1 and the spelling of the critical string on saccade lengths into or first fixation positions on the critical string. This issue will be discussed in detail in Section 5.4.

In addition, there were no effects of spelling preview on the direction of initial refixations. These results suggest that the effects of orthography and misspellings on refixation directions in the other Experiments reported in this thesis are due to foveal, rather than non-foveal, processing.

5.3: Supplementary Analyses of Experiment 6

The experimental materials for Experiment 7 were intermingled with experimental materials for another experiment which included a measure of preview benefit. In this experiment in two of the conditions letter strings like "gtcw" were presented in non-foveal vision and changed before they were directly fixated. At the end of the experiment participants were asked if they noticed anything odd during the experiment and 19 of the participants included in the main analyses above said they did. Some participants reported noticing nonsense letter sequences whilst others were not aware of exactly what had changed. Some reported noticing something only occasionally, whereas others reported that they often noticed something odd. However, due to the intermingling of the stimuli it is impossible to say whether only the four letter nonsense letter strings were noticed or whether the single letter spelling changes in the present experiment were noticed too. Nevertheless, such reports were taken to indicate that perhaps these participants had at least detected some aspect of the saccade contingent change.

It is not clear why some participants seem to potentially detect the change and others do not. One possibility is that individuals have varying degrees of non-foveal awareness. Those with high non-foveal awareness may have been able to preprocess the critical string, before it was directly fixated, to such a level that they were consciously aware of the nature of the preview. Hence those participants with high non-foveal awareness may have been more likely to report noticing something odd during the experiment. Another possibility is that, as explained in Section 1.3.1, the two eyes might not fixate at the same position (Bassou et al., 1993; Cornelissen et al., 1993; Heller & Radach, 1995, 1999; Hendriks, 1996; Radach et al., 1996; Ygge & Jacobson, 1994). Therefore it is possible that some participants may have been reading the sentence whilst their eyes were crossed, that is, the left eye may have been looking further along the text than the right eye. Remember that only the movements of the right eye were monitored, and the saccade contingent change occurred when the right eye crossed the invisible boundary just before the critical string. It is possible that the right eye could be fixating word n-1, the contingent change will not have been triggered, but the left eye could be fixating the critical string. Therefore those participants who seem to potentially detect the changes may have been fixating the misspelled word with their left eye before their right eye crossed the boundary and the preview changed. Consequently, perhaps because some individuals have better non-foveal vision, or because their eyes do not fixate the same position, some participants seem to potentially detect the changes whilst others do not. Note that whatever the reason is for these individual differences, current models of eye movements in reading do not account for them.

The experimental materials that were intermingled with those for Experiment 7 showed qualitatively different results for participants who potentially detected the changes compared to the overall data set. Furthermore, it is possible that those participants who potentially detected the changes may have been better able to use the orthographic characteristics of the critical string to influence where they first fixated it. That is, if participants have better non-foveal vision or if they fixated the critical string before the change, the greater processing of the critical string may have enabled the orthography of the critical string to influence saccade programming. Therefore, a very strong test of the hypotheses tested in Experiments 6 and 7 would be an analysis of only those participants who did not detect the changes. That is, these participants may have been less likely to fixate the critical string before the change was triggered and they may have reduced non-foveal processing ability. Consequently, if the orthography of the critical strings influences fixation positions for these participants, and the effects do not interact with foveal load, then the analysis would provide very strong support for the claim that the results of Experiment 6 are due to non-foveal influences on saccade programming.

Twenty-five of the participants in the analyses above did not detect the changes and for each of the four counterbalanced lists there were at least five of these participants. The most important analyses involving the contingent change were the effects of spelling on the initial fixation positions on the critical string and preview benefits on the critical string. In addition, analyses for parafoveal-on-foveal effects were performed to give an indication of whether detection of the changes might be related to these effects. These results were re-calculated on the basis of twenty participants who did not detect the changes.[6]

5.3.1: Results

Parafoveal-on-foveal effects. Table 5.14 shows the mean reading times on word n-1 and the mean fixation durations prior to fixating the critical string. There were no effects of spelling preview on first fixations or gaze durations on word n-1 (F's < 1) and no interactions between spelling preview and word frequency for first fixations (F's < 1) or gaze durations, F_1 (1, 19) = 1.85, p = .223, MSE = 1541; F_2 < 1.2, on word n-1. There were also no effects of spelling preview on fixation durations prior to fixating the critical string for all the data, saccades launched from word n-1 and saccades launched from three or less characters before the beginning of the

[6] For the analyses based on 20 participants for saccades launched from word n-1, the items analyses were based on data from 46 items because two items did not have data for all four of the conditions.

critical string (*F*'s < 1) with no interactions between spelling and frequency (*F*'s < 1.3). Therefore, in contrast to the entire data set, those participants who did not detect the changes did not show any parafoveal-on-foveal effects on prior fixation durations. However, due to the reduced number of participants in this analysis these data should be interpreted with caution. It is not clear whether the null effect was due to factors such as reduced non-foveal awareness or to differences in power between the two analyses.

Table 5.14 *Experiment 7. Mean First Fixation Duration (FF) and Gaze Duration (GD) on Word n-1. Fixation Duration Prior to Fixating the Critical String (Fixation n-1) for All the Data (All), for Saccades Launched from Word n-1 (n-1) and Saccades Launched from Three or Less Characters from the Beginning of the Critical String (≤3). Data for the 20 Participants in Experiment 7 Who Did Not Detect the Changes. Standard Deviations in Parentheses.*

Experiment 7, n=20		Word n-1		Fixation n-1		
Word n-1	Critical string	FF	GD	All	n-1	≤3
Frequent	Correct	272 (90)	314 (136)	270 (95)	285 (97)	278 (100)
	Misspelled	273 (94)	322 (178)	271 (99)	282 (93)	278 (103)
Infrequent	Correct	302 (97)	381 (174)	299 (100)	313 (94)	308 (83)
	Misspelled	304 (118)	364 (168)	300 (107)	314 (105)	322 (112)

Table 5.15 *Experiment 7. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String. Data for the 20 Participants in Experiment 7 Who Did Not Detect the Changes.*

Experiment 7, n = 20		Critical String		
Word n-1	Critical string	FF	GD	TT
Frequent	Correct	307 (95)	382 (185)	452 (248)
	Misspelled	304 (103	373 (128)	440 (201)
	Preview benefit	-3	-9	-2
Infrequent	Correct	330 (135)	420 (185)	523 (280)
	Misspelled	336 (125)	431 (203)	534 (302)
	Preview benefit	6	11	11

Reading time measures: *Spelling of the critical string*. Table 5.15 shows the mean reading times on the critical string for the 20 participants who did not detect the changes. There were no significant effects of spelling preview on first fixations, gaze durations or total time on the critical string (F's < 1).

Table 5.16 *Experiment 7. Mean First Fixation Duration (FF), Gaze Duration (GD) and Total Time (TT) on the Critical String for Those Cases in Which a Single Fixation was Made on Word n-1 and no Regressions Were Made from Word n-1 on First Pass. Data for the 20 Participants in Experiment 7 Who Did Not Detect the Changes. Standard Deviations in Parentheses.*

Experiment 7, n = 20		Critical String		
Word n-1	Critical string	FF	GD	TT
Frequent	Correct	312 (102)	285 (96)	460 (270)
	Misspelled	315 (116)	288 (84)	439 (199)
	Preview benefit	3	3	-21
Infrequent	Correct	343 (148)	322 (84)	529 (274)
	Misspelled	363 (126)	325 (94)	546 (235
	Preview benefit	20	3	-17

Reading time measures: *Foveal and non-foveal load*. There were no interactions between the frequency of word n-1 or the spelling preview of the critical strings for first fixations (F's < 1), gaze durations, F_1 (1, 19) = 1.63, p = .217, MSE = 3492; F_2 < 1, or total time (F's < 1) on the critical string. As for the analyses for 44 participants, the reading times on the critical string were also calculated in order to provide the optimal conditions for modulation of preview benefit by foveal load. Table 5.16 shows the mean reading time measures for cases in which a single fixation was made on word n-1 and no regressions were made out of word n-1 on first pass[7]. There were no effects of spelling on first fixations, F_1 (1, 18) = 1.75, p = .203, MSE = 1591; F_2 < 1, gaze durations (F's < 1) or total time (F's < 1) and there were no interactions between the frequency of word n-1 and the spelling of the critical string on these measures (F's < 1.2). Therefore, for the 20 participants who did not detect the

[7] The analyses of reading times on the critical string for cases in which a single fixation was made on word n-1 and no regressions were made out of word n-1 on first pass were based on 19 participants and 44 items because one participant and four items did not have data for all four of the conditions.

changes, there were no main effects of preview benefit and no modulation of the amount of preview benefit by foveal load.

Similar to the analyses of parafoveal-on-foveal effects, it is unclear whether the absence of preview benefit effects indicates that the participants who did not detect the changes behaved any differently to those that may have done. That is, the absence of preview benefits might indicate that the participants who did not detect the changes also did not preprocess and integrate orthographic information across fixations. Alternatively, preview benefit effects might simply be quite small and the smaller number of subjects in this analysis may not have provided sufficient power to reflect the effects of preview benefit.

Table 5.17 *Experiment 7. Mean Landing Positions, Incoming Saccade Extents and Launch Sites for Saccades Launched from Word n-1. Data for the 20 Participants in Experiment 7 Who Did Not Detect the Changes. Standard Deviations in Parentheses.*

Experiment 7, n = 20		Landing	Saccade	Launch site
Word n-1	Critical string	position	extent	
Frequent	Correct	4.6 (1.6)	8.1 (1.5)	3.4 (1.2)
	Misspelled	4.2 (1.5)	7.6 (1.6)	3.4(1.3)
Infrequent	Correct	4.2 (1.7)	7.7 (1.7)	3.5 (1.2)
	Misspelled	3.9 (1.6)	7.4 (1.7)	3.5 (1.3)

Fixation positions: *Spelling of the critical string preview.* Table 5.17 shows the mean landing positions, saccade lengths and launch sites for the critical string for saccades launched from word n-1. For saccades launched from word n-1, mean first fixation landing positions were significantly nearer the beginning of the misspelled critical string ($M = 4.0$, $SD = 1.6$) compared to the correctly spelled critical string ($M = 4.4$, $SD = 1.7$), F_1 (1, 19) = 7.85, $p = .01$, $MSE = 0.34$; F_2 (1, 45) = 8.25, $p < .01$, $MSE = 1.03$. Also, mean saccades to the critical word tended to be shorter if the critical word was misspelled ($M = 7.5$, $SD = 1.7$) compared to when it was spelled correctly ($M = 7.9$, $SD = 1.6$), although this difference was significant across items, F_2 (1, 45) = 8.32, $p < .01$, $MSE = 0.88$, but not participants, F_1 (1, 19) = 3.44, $p = .079$, $MSE = 0.39$. There were no differences in mean launch sites when the critical string preview was correctly spelled ($M = 3.5$, $SD = 1.2$) compared to when it was misspelled ($M = 3.5$, $SD = 1.3$), F_1 (1, 19) = 1.36, $p = .259$, $MSE = 0.16$; $F_2 < 1$.

Therefore landing positions were, and saccade lengths tended to be, influenced by non-foveal processing difficulty. The fact that the landing position effects hold for the participants who did not detect the changes has two possible implications. First, the effects hold for participants who may have reduced awareness of non-foveal characteristics. Secondly, the fact that the effects hold for such a reduced data set indicates that the effects of orthography on saccade programming are clearly robust.

Fixation positions: Foveal and Non-foveal Load. Figures 5.14 and 5.15 show the mean landing positions on and saccade lengths into the critical string for each condition for the 20 participants who did detect the changes. There were no interactions between the spelling of the critical word and the frequency of word n-1 for saccade lengths, landing positions, or launch sites (*F*'s < 1). Therefore, similar to both Experiments 6 and 7, there was no evidence of an interaction between foveal and non-foveal processing difficulty on fixation positions on the critical string.

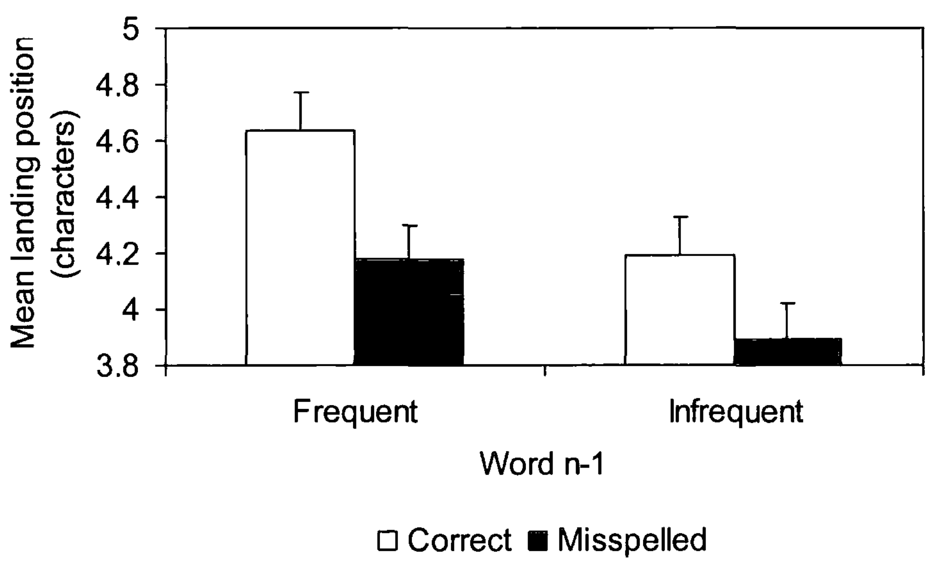

Figure 5.14 Experiment 7. Mean first fixation landing positions (+*SE*) on the critical string for the 20 participants who did not detect the saccade contingent changes.

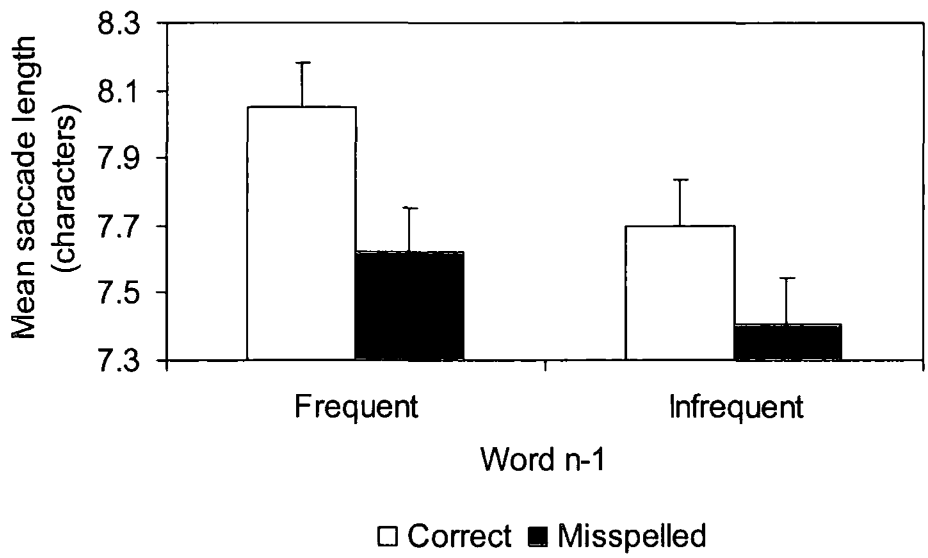

Figure 5.15 Experiment 7. Mean saccade lengths (+*SE*) into the critical string for the 20 participants who did not detect the saccade contingent changes.

5.3.2: Discussion

In contrast to the full data set for Experiment 7, there were no parafoveal-on-foveal effects and no significant preview benefit effects. However, these non-significant effects should be treated with caution because the reduced data set necessarily had a lot less power than the full data set.

Importantly, the effects of spelling and the lack of an interaction between spelling and the frequency of word n-1 are in line with the results of both Experiment 6 and the analyses of the full data set for Experiment 7. Therefore, even for participants who may have had reduced non-foveal processing ability, and who were unlikely to have fixated the critical string before the change occurred, non-foveal orthography influenced saccade programming independent of foveal processing load.

5.4: Discussion of Experiments 6 and 7

Experiments 6 and 7 provided three tests of Hyönä and Pollatsek's (2000) processing difficulty hypothesis, the third of which has important implications for general linguistic processing accounts as a whole. The first test of Hyönä and Pollatsek's account was that foveal processing difficulty should reduce non-foveal processing and consequently shorten saccades to the following word. In line with this prediction, saccade lengths from word n-1 to the critical string were significantly shorter when word n-1 was infrequent compared to when it was frequent. However an alternative interpretation of this result is that when the foveal word is more difficult to process, more refixations are planned on this word and so it is likely that more intended refixations will overshoot and land at the very beginning of the following word. As explained in Section 5.1.3, descriptive results for Experiment 6 were suggestive of this possibility, but similar results for Experiment 7 (see Section 5.2.3) are more ambiguous. Further support for foveal processing difficulty producing shorter subsequent saccades is provided by the finding that rightward refixation saccades are shorter on orthographically irregular compared to regular beginning words (Experiments 4 and 5, Chapter 4). However note that because the processing difficulty hypothesis only accounts for differences in saccade lengths, and not the decision to make a progressive or regressive saccade, it can not explain the effects of orthography on the direction of refixation saccades from the initial fixation position.

The second test of the processing difficulty hypothesis was that non-foveal processing difficulty should reduce non-foveal processing and consequently shorten saccades. The results of Experiments 6 and 7 support the findings of Experiments 1, 4 and 5, previous sentence reading studies (Hyönä, 1995; Radach et al., in press; Vonk et al., 2000), and other attraction and general linguistic processing accounts which suggest that non-foveal orthographic processing difficulty can influence fixation positions. However Hyönä and Pollatsek (2000) specifically predict that non-foveal processing difficulty should shorten saccade lengths. Although the spelling of the critical word clearly influenced landing positions on the critical word, the effects on saccade lengths into the word were not reliable. It is possible that differences in launch site also influenced fixation positions. As explained in Section 1.3.3, saccades might be attracted by orthographically irregular letter sequences from more distant launch sites and, as a result of the range effect (see Section 1.3.1) this might influence fixation positions on the critical string. However there were no clear effects of orthography on refixation or skipping probabilities prior to fixating the critical string and there were certainly no consistent patterns in these probabilities across the two Experiments. Therefore if there is an influence of launch site, it is quite unclear how this effect is produced.

The third prediction of Hyönä and Pollatsek's (2000) processing difficulty hypothesis is that the effects of foveal and non-foveal processing difficulty should interact. Other general linguistic processing accounts (Radach et al., in press; Rayner & Morris, 1992) might make similar predictions. That is, when foveal processing is difficult, non-foveal processing is reduced and so the effects of non-foveal processing difficulty on saccade lengths should be smaller compared to when foveal processing is easy. However, both Experiments 6 and 7 showed no interaction between the effects of foveal and non-foveal processing difficulty on saccades into the critical string.

There are at least three possible explanations for the absence of the predicted interaction between foveal and non-foveal processing difficulty. First, foveal and non-foveal processing difficulty may both reduce non-foveal processing and shorten saccades, but these effects might be independent. For example, there might be parallel processing and additive effects of foveal and non-foveal processing difficulty. However, the general linguistic processing accounts explain word skipping in the same manner as they explain differences in landing positions. Therefore if the general linguistic processing accounts were to predict non-foveal influences on landing positions independent of foveal processing difficulty then they should also predict effects of skipping independent of foveal processing difficulty. However, as outlined in the introduction to this Chapter, it seems likely that word skipping is modulated by foveal processing difficulty (see also Kennison & Clifton, 1995).

A second possibility is that foveal processing difficulty might only influence some types of non-foveal processing such that this impacts on saccade lengths. For example, foveal processing difficulty might reduce non-foveal morphological preprocessing (Hyönä & Pollatsek, 1998) but it might not limit non-foveal orthographic preprocessing (as shown by differences in saccade lengths). Therefore the influence of non-foveal morphology on saccade programming may be influenced by foveal processing load. In contrast, the influence of orthography on saccade programming might be determined by quite different processes, such as those suggested by the attraction (e.g. Hyönä, 1993) or visual processing (e.g. Findlay & Walker, 1999) explanations. However note that the general linguistic processing accounts do not specify exactly what kinds of non-foveal information might influence fixation positions. For example, it must be assumed that the orthographically familiar misspellings in Experiments 2 and 3 (Chapter 3) did not induce sufficient non-foveal processing difficulty to influence saccade programming.

A third possible explanation for the absence of an interaction between foveal and non-foveal processing difficulty on saccade programming might be related to the fact that Experiment 7 also showed no such interaction for reading times on the critical string. That is, preview benefit derived from the critical string was also independent of foveal processing difficulty. These results suggest that foveal processing difficulty does not reduce orthographic non-foveal processing. Consequently it is possible that, contrary to the fundamental assumption of the processing difficulty hypothesis, the claims of Henderson and Ferreira (1990), and the basis of some models of eye movements in reading (e.g. Reichle et al., 1998) foveal processing load does not modulate non-foveal processing. This matter is so fundamental to the issue of eye movements in reading that further evidence is clearly needed before any strong claims can be made. Furthermore, it would be necessary to establish whether non-foveal preprocessing for integration across saccades (preview benefit) was modulated by foveal load in the same way as the decision of which word to fixate (word skipping). For example, general processing load could influence reading strategies which might influence skipping rates over a series of fixations (O'Regan, 1990), rather than foveal processing load having immediate effects on skipping of the following word. If foveal load did not modulate word skipping directly then there might be parallel and independent processing of foveal and non-foveal text, as outlined in the first suggestion.

To summarise, the general linguistic processing accounts might provide an accurate account of the influence of orthography on saccade programming if the influences of foveal and non-foveal processing are independent. Further studies are required to investigate this issue. However if it is assumed that word skipping is influenced by local text processing load, and that the general linguistic processing accounts must explain differences in fixation positions on a similar basis, then the results of Experiment 7 are clearly incompatible with the predictions of these accounts. Instead, it might be suggested that the general linguistic processing explanations might account for some types of non-foveal influences on fixation positions, such as the characteristics of morphological constituents. However, orthographic influences on fixation positions might be explained by different processes such as those suggested by the attraction hypotheses.

5.5: Conclusions

Experiments 6 and 7 show that orthography influences where words are first fixated, in line with the results of Experiments 1, 4 and 5. The misspellings also influenced the direction of refixation saccades as shown in Experiments 1 and 3. Experiment 7 showed some evidence of parafoveal-on-foveal effects which might be attributed to oculomotor error, Experiment 6 showed no such effects. Experiment 7 showed that non-foveal orthographic information can be preprocessed and integrated across saccades, but there was no evidence to suggest that this was modulated by foveal load. Importantly, both Experiments 6 and 7 showed no interaction between foveal and non-foveal processing difficulty on saccade lengths or fixation positions. Therefore any effects of foveal and non-foveal processing on these measures must be independent.

Chapter 6

General Discussion

The final Chapter reviews the main findings, and the implications for current models of eye movements and saccade programming, for each of the issues addressed in this thesis. Section 6.1 examines what determines where words are first fixated. Section 6.2 discusses what determines the direction and length of refixation saccades. Section 6.3 examines whether non-foveal preprocessing can influence eye movement behaviour before the preprocessed words are fixated. Section 6.4 discusses a number of general phenomena shown in this thesis. Finally, in Section 6.5 the main theoretical implications are summarised and the final conclusions are formed.

6.1: What Determines Where Words are First Fixated

The General Introduction (Chapter 1) argued that there is a lot of evidence to suggest that both visual and linguistic information is preprocessed in non-foveal vision (Section 1.1) and that both these types of information can be used to influence which words are fixated (Section 1.2). However, it was shown that there is very little evidence to suggest that processing beyond the level of word length can influence where words are first fixated (Section 1.3). Three studies (Hyönä, 1995; Vonk et al., 2000; Radach et al., in press) have shown that first fixations land nearer to the beginning of orthographically irregular, compared to orthographically regular, beginning words in sentences. However, all three of these studies were undertaken in languages other than English and it is not clear whether individual letter frequency was controlled in all these experiments. Furthermore, a number of studies have failed to show effects of orthography on initial fixation positions (Kennedy, 1998, 2000b; Liversedge & Underwood, 1998; Radach et al., 1995; Radach & Kempe, 1993; Radach & McConkie, 1998). It is unclear whether the inconsistencies between the findings of these studies might have been due to the use of insufficiently strong manipulations of orthography, differences between languages, or because the effect of orthography on fixation positions was simply not robust. This thesis therefore aimed to address whether orthography does influence initial fixation positions on words and how these effects might be explained. Section 6.1.1 summarises the results, Section 6.1.2 discusses possible explanations for the effects and Section 6.1.3 considers how general models of eye movements in reading might incorporate these explanations.

6.1.1: Summary of results

The results of five experiments showed that the orthographic characteristics of words influence where they are first fixated in English. Experiment 1 (Section 2.1) and Experiments 6 (Section 5.1) and 7 (Section 5.2) showed that first fixations land nearer to the beginning of words that are misspelled to create orthographically irregular initial letter sequences compared to correctly spelled words with orthographically regular initial letter sequences. Similarly, Experiments 4 (Section 4.1) and 5 (Section 4.2) showed that first fixations land nearer to the beginning of correctly spelled words with orthographically irregular, compared to orthographically regular, initial letter sequences. Experiments 4 and 5 carefully controlled for individual letter frequency, therefore the results must be explained by preprocessing of letter sequences rather than individual letters. The results therefore provide strong evidence that preprocessing of orthography does influence where words are first fixated in the reading of English sentences. It is clear that, if sufficiently strong manipulations of orthography are used, those manipulations will influence saccade programming in English, even if the size of the effects is actually quite small (half a character or less).

As explained in Section 1.3.1, the differences in landing positions caused by preprocessing of orthography must be explained by either, or both, differences in saccade lengths and launch sites. Experiment 5 showed that saccades were significantly longer into orthographically regular than irregular beginning words. Furthermore, all of the other experiments which show effects of orthography on landing positions also show similar (though non-significant or non-reliable) trends for longer saccade lengths into orthographically regular than irregular beginning words. Experiment 7 produced a significant effect of launch site such that launch sites were significantly further away from misspelled critical strings than for correctly spelled critical strings. Experiments 4 and 6 also produced non-significant mean launch site differences consistent with this pattern. However Experiments 1 and 5 showed no consistent differences in the pattern of launch sites. Nevertheless, mean differences in landing positions must often be accounted for by numerical differences in both saccade lengths and launch sites. Therefore differences in launch site may contribute to the landing position effects in some way.

One way in which the characteristics of a word might have an effect on launch site is by influencing the fixation probabilities prior to fixating the critical word. For example, saccades might be attracted to orthographically irregular letter sequences from distant launch sites such that the probability of skipping the previous word is increased and refixating the previous word is reduced. Such categorical differences in fixation probabilities would produce differences in launch sites (see Section 1.3.1) which would influence landing positions. Such differences in fixation probabilities might be indicative of discrete, rather than graded, influences on saccade programming. That is, preprocessing of orthography might produce a categorical decision about which word to fixate, the actual landing position would not be sensitive to the degree of orthographic regularity. Previous studies of orthographic landing position effects have not provided comprehensive analyses of launch sites (see Table 1.1), and skipping and refixation probabilities for the previous word. All three of these measures were tested in each of the five experiments showing orthographic landing position effects in this thesis.

Experiment 1 showed that word n-1 was more likely to be skipped when the critical string was misspelled compared to when it was spelled correctly. This result is consistent with the notion that saccades might be attracted from more distant launch sites, and with similar findings shown by Hyönä and Bertram (in press a). However, Experiments 6 and 7 showed no such effects with similar manipulations and Pynte et al. (in press) reported that irregular misspellings reduce, not increase, the probability of skipping the previous word. In addition, Experiment 6 showed that word n-1 tended to be more likely to be refixated if the critical string was misspelled compared to if it was spelled correctly. This pattern of results is opposite to that which might be expected if refixation probabilities were to explain the landing position effects. That is, if orthography attracted saccades from different launch sites, this should decrease, not increase, the probability of refixating word n-1 when the critical string is orthographically irregular. Furthermore, the unreliable differences in refixation probabilities in Experiment 6 should be interpreted with great caution because none of the other Experiments (1, 4, 5 and 7) showed similar results despite the very similar manipulations.

To summarise, although there are clear effects of orthography on landing positions, there are no reliable effects of either saccade length or launch site. Nevertheless, although the effects of saccade length are not always significant, there is a consistent pattern such that saccade lengths are shorter into irregular than regular beginning words. Therefore, the results do suggest that differences in saccade length contribute to the differences in landing positions. In contrast, although in some cases differences in launch site also appear to contribute to the effect, the pattern of these differences is not as consistent across the Experiments. In addition, there are no clear explanations for differences in launch sites, such as attraction processes producing differences in fixation probabilities prior to fixating the critical word. Therefore, there is no clear evidence for discrete effects of orthography on saccade programming, the small shifts in the preferred viewing positions are more suggestive of a graded effect.

Experiments 1, 4, 5, 6 and 7 show that the orthographic characteristics of words influence where words are first fixated. Experiments 2 (Section 3.1) and 3 (Section 3.2) investigated whether lexical preprocessing of words can also influence saccade programming. These Experiments were designed to investigate why words that were misspelled to create high frequency initial letter sequences in Experiment 1 produced different fixation positions compared to correctly spelled words. Experiment 2 showed that preprocessing of any kind of illegality within words can not influence where words are first fixated. Experiment 3 showed that the informativeness of word initial letter sequences also can not influence first fixation positions on words. On the basis of these two experiments it was concluded that lexical influences on fixation positions, such as that shown in the high frequency misspelling condition in Experiment 1, are at best unreliable and possibly spurious.

The results of Experiment 2 in particular contrast with earlier claims that the distribution of informative letter sequences within words can influence where they are subsequently fixated (Everatt & Underwood, 1992; Hyönä et al., 1989; Underwood et al., 1990; Underwood et al., 1987). Previous studies examining the effects of informativeness on fixation positions confounded the variable of informativeness with differences in orthographic familiarity. In addition, studies that have examined the effects of orthographic regularity on fixation positions have necessarily confounded the variable of regularity with informativeness in order to generate sufficiently strong manipulations of orthographic regularity. Therefore although these studies claim that informativeness or orthography influence fixation positions, it is possible that either of these variables might explain all of the effects. Importantly, Experiment 2 shows that strong manipulations of informativeness, with orthographic familiarity controlled, did not influence fixation positions. This result suggests that orthography, not lexical preprocessing, is the variable that can influence where words are first fixated.

The absence of a lexical influence on fixation positions is consistent with the idea that different types of processes are sensitive to different kinds of preprocessing, as discussed in the Section 1.2.4. In support of previous studies, Experiment 7 showed that frequent words are more likely to be skipped than infrequent words (Radach & Kempe, 1993; Rayner & Fischer, 1996; Rayner et al., 1996). Therefore, lexical information can be preprocessed such that it influences which words are fixated, but it is not used to influence where words are first fixated. Perhaps large discrete shifts of attention that might be associated with which word to fixate (e.g. Morrison, 1984) are sensitive to general linguistic processing, whilst small graded influences on fixation positions are only sensitive to simple types of preprocessing such as orthography.

Experiment 5 (Section 4.2) and Experiments 6 and 7 were designed to test possible explanations for the influence of orthography on initial fixation positions. Experiment 5 showed that the effects of orthography on fixation positions holds for text presented in upper case. Experiments 6 and 7 showed that the influence of orthography on fixation positions is independent of processing difficulty on the prior fixation. The implications of these results for explanations of the effects of orthography on saccade programming will be discussed in the following Section.

To summarise, the experiments in this thesis provide clear evidence that orthography influences where words are first fixated in the reading of English sentences. There are consistent, though often non-significant, effects of saccade length to account for these differences in landing position. The effects of orthography hold regardless of which case the text is presented in, and regardless of foveal processing load on the previous fixation. Although preprocessing of lexical information may influence word skipping, such preprocessing does not influence initial fixation positions on words.

6.1.2: Explanations for how orthography influences where words are first fixated

As explained in Section 1.3.3, a number of explanations have been proposed to explain the effects of orthography on where words are first fixated. These can be broadly classified as visual processing, attraction, or general linguistic processing based accounts. Each of these will be evaluated in relation to the results presented in this thesis.

Reichle et al. (in press) suggested that low spatial frequency information might be used to programme saccades, such as the presence or absence of ascenders and descenders. However Experiment 5 showed that orthography influences fixation positions for upper case text, which suggests that preprocessing of orthography for saccade programming does not require the visually distinctive letter and word shape cues found in lower case text. Furthermore, the fact that exposure to upper case text is generally less than that for lower case text, and yet reading measures for the two are largely the same, suggests that the same processes, such as abstract preprocessing of non-foveal letter sequences, are involved in reading both kinds of text. If non-foveal preprocessing of orthography in order to influence saccade targeting was based on abstract codes, then this would be inconsistent with suggestions that the effects of orthography on fixation positions are visually based. For example, Findlay and Walker's (1999) suggestion that the intrinsic salience (visual familiarity) of letter sequences can influence saccade programming. Nevertheless, it is possible that visual familiarity of letter sequences mediates the effect of orthography on saccade programming in both lower and upper case text. Furthermore, these visually based accounts are consistent with the results of Experiments 6 and 7 which show that the effects of orthography on landing positions are independent of processing load.

Other explanations of the effects of orthography on fixation positions can largely be classified as attraction or general linguistic processing based accounts. These will be discussed in turn in some detail. As explained in Section 1.3.3, the original attraction hypotheses (Hyönä, 1993; McConkie, 1979; Underwood et al., 1990) suggested that saccades were directed to salient features or regions of processing difficulty. Such an account might predict an increase in the number of fixations at the location of orthographic irregularity. However, landing position distributions in previous studies (Radach et al., in press; Vonk et al., 2000) and for the experiments in this thesis show a much more graded effect of orthography such that there is a small shift in the whole of the preferred viewing position. Instead, as suggested by Beauvillain and Doré (1997), irregular letter sequences might act to modify the word length (and launch site) based saccade computation, such that there is a small shift in the preferred viewing position in the direction of the irregularity. The attraction accounts might also predict differences in launch sites if saccades are attracted to orthographically irregular letter strings. However, there were no clear effects of orthography on either launch sites or fixation probabilities prior to fixating the critical word. Nevertheless, the results are generally consistent with an attraction based account, in which the attraction processes influence the word length and launch site based saccade computation such that orthographically irregular beginning words produce a small shift in the preferred viewing position.

It has been suggested that attraction of saccades might be mediated by localised processing difficulty (McConkie, 1979) or salient "pop-out" (Beauvillain & Doré, 1997; Hyönä, 1993b). The notion that saccades are directed to the location of attention is consistent with serial attention shift accounts of eye movements in reading (Morrison, 1984; Engbert & Kliegl, 2001; Engbert et al., 2002; Reilly & Radach, 2003), many visual perception studies (Rizzolatti et al, 1987; Deubel & Schneider, 1996, Hoffman and Subramaniam, 1995; Kowler et al., 1995; Shepherd et al., 1986; but see Stelmach et al., 1997), and recent experiments using letter strings in artificial tasks (Doré & Beauvillain, 1999; Doré-Mazars et al., 2002) (as discussed in Section 1.3.3). However, although saccades might be directed to the locus of attention just before the saccade is executed, selection of the saccade target is not necessarily dependent on the distribution of attention (general processing resources) as McConkie might suggest. In support of this, the results of Experiment 7 suggest that the effects of orthography are not limited by foveal attentional resources. Inhoff, Starr et al. (2000) suggested that some types of non-foveal information, such as orthography, might be processed before attention has shifted to that location, presumably independent of processing load. In addition, on the basis that the influence of orthography on saccade programming occurs earlier, rather than later, in a fixation (see Section 1.3.3), Doré and Beauvillain (1998) suggested that saccade programming might be mediated by preattentive processing of orthography. "Preattentive" processing might be interpreted as automatic processing, independent of processing load. However, if saccade target selection is independent of processing load, this does not preclude the possibility that just before the saccade is executed "attention" (processing resources) is directed to the saccade target.

Therefore the results suggest that the word length and launch site based saccade programme can be modified as a result of preprocessing of orthography independent of processing load. Although it has been suggested that irregular orthography might attract saccades by "popping-out" of non-foveal text (Beauvillain & Doré, 1997; Hyönä, 1993b), the small shifts in the preferred viewing position (as noted above) suggest that orthography produces a small influence on the whole of the landing position distribution rather than attracting saccades to a particular location. Furthermore, if the effects of orthography were based on visual familiarity, as Findlay and Walker (1999) suggest, the notion of orthography producing "pop-out" might be feasible. However Radach et al. (in press) questioned whether sufficiently fast and parallel processing of text is possible in order that text might "pop-out" on the basis of linguistic processing.

To summarise, the results are largely in support of the attraction hypotheses. Specifically, the results suggest that preprocessing of orthographically irregular word initial letter sequences influences the word length and launch site based saccade computation such that there is a shift in the whole of the landing position distribution in the direction of the irregularity. The attraction hypothesis could potentially have explained differences in launch site, but the results produced no clear effects of launch site. Importantly, although saccades might be directed to the location of attention just before execution of the saccade, the influence of orthography on saccade programming is independent of general processing load. As a result, it seems unlikely that orthography attracts saccades on the basis of localised processing difficulty (McConkie, 1979). In addition, it might be considered unfeasible that orthographic processing produces "pop-out" to attract saccades (Beauvillain & Doré, 1997; Hyönä, 1993). Consequently a different kind of attraction hypothesis is required and a possible architecture for such an account is suggested in Section 6.1.3 and expanded in Section 6.5.1.

An alternative explanation to the attraction hypothesis is that general linguistic processing influences saccade programming. Hyönä and Pollatsek's (1998, 2000) extent of processing account will be evaluated first, followed by other accounts which suggest that the same processes that determine word skipping might also influence fixation positions (Radach et al., in press; Rayner & Morris, 1992). Hyönä and Pollatsek proposed that foveal and non-foveal processing difficulty modulate the perceptual span, and the extent of non-foveal processing determines the saccade target. In support of Hyönä and Pollatsek's hypothesis, Experiments 6 and 7 showed that foveal processing difficulty modulates, and non-foveal processing difficulty tends to modulate (at least numerically), saccade lengths to the following word. However there are a number of problems with Hyönä and Pollatsek's suggestion.

First, the processing difficulty hypothesis does not explain why the differences in landing positions are not entirely accounted for by differences in saccade lengths. Secondly, the hypothesis does not specify exactly what kinds of information might induce non-foveal processing difficulty. For example, it must be assumed that the orthographically familiar misspellings in Experiments 2 and 3 (Chapter 3) did not induce sufficient non-foveal processing difficulty to influence saccade programming. Thirdly, the descriptive results of Experiment 6 are consistent with the possibility that the effects of foveal load on saccade lengths into the following word might be due to overshooting of refixations rather than reductions in non-foveal processing limiting saccade lengths. Fourthly, the results of Experiments 6 and 7 show that the effects of non-foveal orthographic processing difficulty on saccade programming are not modulated by foveal processing difficulty. As explained in Section 5.5, such results are inconsistent with an extent of processing account (Hyönä & Pollatsek, 2000) in which foveal and non-foveal processing difficulty impact on the same processes and in which the fixated word is processed in preference to the non-foveal word.

The absence of an interaction between foveal and non-foveal processing difficulty is not necessarily inconsistent with the general idea of saccades being driven by extent of processing. Saccade programming could be mediated by the extent of non-foveal processing which is limited only by non-foveal, rather than foveal, processing resources. As suggested in Section 5.4, such non-foveal processing could be undertaken in parallel with foveal processing. Alternatively, it is possible that foveal load only impacts on certain types of non-foveal processing. For example, foveal processing difficulty might limit processing of the characteristics of non-foveal morphological constituents (as shown by Hyönä & Pollatsek, 1998) but not non-foveal processing of orthography. Overall, it seems plausible that the extent of processing account might explain effects of complex linguistic processing, such as the characteristics of morphological constituents, on saccade programming. However other types of non-foveal processing, such as orthographic processing, might proceed independently of general processing difficulty and might influence saccade programming in a quite different manner.

Other accounts of saccade programming, based on the idea that the same processes that determine word skipping also influence fixation positions, might also predict smaller effects of orthography with high foveal processing load. Rayner and Morris (1992) suggested that frequent letter sequences within words might be skipped. It seems likely that such a skipping mechanism would be linked to general sentence processing rather than just saccade programming to the following word (e.g. Reichle et al., 1998). Similar to Rayner and Morris, Radach et al. (in press) suggested that the same mechanism that determines which word is fixated might also influence where words are first fixated. Radach et al. proposed that the Glenmore model (Reilly & Radach, 2003) might be modified such that linguistic processes influence activation of letters, as well as words, within a salience map which then determines the saccade target. As a result of limited processing resources, linguistic influences on saccade targeting might be reduced when foveal processing load is high. Therefore both Rayner and Morris and Radach et al.'s suggestions seem incompatible with the finding that foveal load does not modulate the effects of orthography on fixation positions.

To summarise, the results of Experiments 6 and 7 simply can not be reconciled with general linguistic processing accounts which might suggest that foveal processing difficulty limits the influence of orthography on fixation positions (Hyönä & Pollatsek, 2000; Radach et al., in press; Rayner & Morris, 1992). Although note that these accounts might still provide the best explanations for effects such as the influence of morphological constituents on saccade programming. In contrast to the general linguistic processing explanations, both the attraction and visual processing based accounts predict that orthography influences saccade programming independent of foveal load. However, the fact that there are effects of orthography on landing positions in both upper and lower case text suggest that the effects might be mediated by abstract, rather than visual, non-foveal preprocessing. Therefore the attraction based accounts seem to provide the best explanations of the effects. However, as explained above, there are problems with previous suggestions about what saccades are attracted to, such as processing difficulty or "pop-out". Therefore, an alternative explanation will be outlined in the next Section.

6.1.3: Implications for models of eye movements in reading

Most models of eye movements in reading do not predict any effects of orthography on initial fixation positions on words. The one exception, the ideal observer model (Legge et al., 1997), suggests that lexical preprocessing influences where words are first fixated. However, although such an explanation might explain orthographic effects on fixation locations, it does not explain why Experiments 2 and 3 showed no effects of lexical preprocessing on saccade targeting. All the other accounts of eye movements in reading which make predictions about where words are fixated suggest that this depends on just visual and oculomotor factors (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990).

The oculomotor accounts (O'Regan, 1990; Reilly & O'Regan, 1998) could not explain orthographic influences on fixation positions without fundamentally changing their assumption that visual and oculomotor factors are the only determinants of where the eyes move in reading. However other models do not have a fundamental objection to linguistic influences on saccade programming, they simply do not attempt to model such effects. Previous research has produced evidence both for and against the influence of orthography on saccade programming, and so it is understandable that the models have not as yet incorporated such predictions. However this thesis now provides strong evidence that non-foveal orthographic regularity can influence where words are first fixated and any comprehensive model of eye movements in reading must now account for these effects. The conclusions of Section 6.1.2 suggest that the models might explain such effects by incorporating some measure of orthographic processing, independent of processing load, which influences saccade programming. Note that such preprocessing of orthography might be available to processes determining saccade programming, but it may not necessarily be integrated across saccades such that it can facilitate processing (increase preview benefit) when the words are subsequently fixated.

The E-Z reader model (Reichle et al., 1999, in press) might be adapted so that the early visual processing system has access to orthographic preprocessing of the following word, independent of attention. Such preprocessing could modify the word length and launch site dominated saccade computation. Radach et al. (in press) suggested that the Glenmore model (Reilly & Radach, 2003) might be adapted such that the linguistic module uses orthographic information to influence the activation of individual letters within the salience map. However, because of processing limitations in the linguistic module, the activation of orthography within the salience map would be restricted by processing load, for example of the fixated word. However, a different account based on the idea that a linguistic module activates words and letters within a salience map might provide a good account of the data. Such an alternative account will be outlined here, expanded in Section 6.2.2 in relation to refixations, and summarised in Section 6.5.1.

It is suggested that the linguistic module might process two kinds of information, resource limited lexical and sub-lexical processes and resource unlimited orthographic familiarity. The resource limited lexical and sub-lexical processes activate non-fixated words within a salience map such that each letter within a word receives the same activation. This suggestion corresponds to that in the Glenmore model and it predicts that frequent and predictable words will be more likely to be skipped. In addition, because processing resources are limited, if there is high processing load then there is less activation of non-fixated words and consequently the probability of word skipping is reduced. However, in this account the linguistic module also processes the familiarity of non-foveal letter sequences, independent of processing resources and limited only by acuity. Therefore each letter within the salience map also receives activation from the linguistic module according to letter sequence familiarity. Therefore selection of the saccade target (the point of maximum salience) depends primarily on activation levels for words (i.e. influenced by word length and launch site), but saccade programming is also weighted by letter sequence familiarity within words.

According to such an account, the orthographic regularity (letter sequence familiarity) within words would influence where words were first fixated, largely as a result of saccades being slightly shortened or lengthened by orthography weighting the word length and launch site based saccade computation. However, it is possible that if a particular letter sequence was especially salient it may attract saccades from more distant launch sites compared to if the word had regular orthography. That is, similar to the attraction accounts, orthography might influence both saccade length and launch site. Section 6.2.2 expands this account to suggest a mechanism for the programming of refixations.

6.2: What Determines Where Words are Refixated

Section 1.4 showed that there was some evidence for linguistic influences on the location (Pynte, 1996, 2000; Pynte et al., 1991; Underwood et al., 1988; Underwood et al., 1987) and length (Hyönä, 1995; Hyönä et al., 1989; Hyönä & Pollatsek, 1998) of refixation saccades. However models of eye movements in reading do not predict such effects. This thesis therefore examined whether the orthographic characteristics or the difficulty of fixated words influences the nature of refixation saccades, Section 6.2.1 summarises these results. Section 6.2.2 discusses possible explanations for the effects and considers how general models of eye movements in reading might incorporate these explanations.

6.2.1: Summary of results

All of the Experiments showed that words that were linguistically difficult to process, due to orthographic regularity, misspellings or word frequency, produced more refixations than words that were easy to process. These results support previous studies showing that the linguistic characteristics of words influence the probability of refixating them (Balota et al., 1985; Inhoff & Rayner, 1986; Rayner et al., 1996).

However in addition to this, the results also suggest that the orthography or difficulty of a word can influence the direction and length of refixation saccades.

Experiments 1, 3 and 6 showed that initial refixations were more likely to be to the left of the initial fixation position if the word initial trigram was misspelled compared to if it was spelled correctly. Note that the misspellings were always towards the word beginning and so such leftward refixation saccades were generally targeted in the direction of the misspellings. In Experiment 7, the critical string was only misspelled in the preview, prior to direct fixation, and under these conditions the misspellings did not influence the direction of refixations. These results suggest that the characteristics of a word can only influence the direction of refixations once the words are fixated. Therefore the effects can not be due to preprogramming of refixations before the critical strings are fixated. However the effects of misspellings on the direction of refixations might be due to processes unusual to normal reading, such as the computation of the correct identity of the foveal misspelled words. Nevertheless, refixation saccades were also more likely to be directed to the left of the initial fixation for orthographically irregular, compared to regular, words in Experiment 4 (similar trends were produced in Experiment 5). In support of previous studies, these results suggest that the linguistic characteristics of words can influence the location of refixations (Pynte, 1996, 2000; Pynte et al., 1991; Underwood et al., 1988; Underwood et al., 1987). The data also suggest that the orthography or difficulty of a word can influence the length of refixation saccades.

Both Experiments 4 and 5 showed that rightward refixation saccades were significantly shorter for irregular compared to regular beginning words. These results are especially interesting because if only visual factors influenced refixation saccades (O'Regan, 1990) then refixation saccades should have been longer, rather than shorter, for the orthographically irregular beginning words. That is, the initial fixation position was nearer the word beginning for orthographically irregular words and so the distance between the initial fixation and the end of the word was longer. If saccades were simply targeted towards the end of the word based only on visual information then refixation saccades should have been longer rather than shorter for orthographically irregular words. These results support previous studies showing that the linguistic characteristics of words can influence the length of refixation saccades (Hyönä, 1995; Hyönä et al., 1989; Hyönä & Pollatsek, 1998).

6.2.2: Implications for models of eye movements in reading

As explained in Section 1.4.2 most models of eye movements in reading provide no clear explanations for how refixation saccades are programmed. The oculomotor accounts (O'Regan, 1990) explain the position of refixations entirely in terms of word length and the position of the initial fixation, however the evidence presented above shows that linguistic factors can also influence refixation saccades. The attraction and general linguistic processing accounts (see Sections 1.3.3 and 6.1.2) of saccade programming might explain such effects.

McConkie (1979) suggested that refixation saccades might be directed to the locus of attention within words. Other attraction based accounts might predict that saccades are directed to salient letter sequences as a result of "pop-out" (Beauvillain & Doré, 1997; Hyönä, 1993b). Such attraction explanations may explain why more saccades were directed to the left of the initial fixation when the word beginnings were orthographically irregular compared to when they were orthographically regular. However, it might be more difficult for attraction accounts to explain why refixation saccades are shorter on orthographically irregular, or more difficult, words. Nevertheless, the orthographic regularity of letter sequences within the words, other than the initial three letters, was uncontrolled. Therefore it is possible that rightward refixation saccades were shorter on orthographically irregular beginning words because these also have orthographically irregular letter sequences near the word centre. Consequently fixations may have been attracted to the orthographically irregular letter sequences near to the right of the initial fixation which may have produced shorter rightward refixation saccades.

Hyönä and Pollatsek's (1998, 2000) processing difficulty account provides an alternative explanation for the differences in refixation saccade lengths. Foveal processing difficulty might reduce the extent of processing within the word, refixation saccades are targeted to this extent of processing, which results in shorter refixation saccades on difficult words. In addition, although the attraction explanations above might explain effects of orthography on refixation saccade lengths, the processing difficulty hypothesis has the advantage of being able to explain the effects of more complex features on saccade lengths such as the characteristics of morphological constituents (Hyönä & Pollatsek, 1998). However, the processing difficulty hypothesis can not explain how the characteristics of a word influence whether the refixation saccade is made to the right or left of the initial fixation position.

The attraction accounts best explain the effects of orthography on the direction of refixations, and the extent of processing accounts best explain the effects of any linguistic characteristic of the fixated word on refixation saccade lengths. Consequently, on the basis of these two different accounts, it is difficult to suggest a parsimonious explanation for how models of eye movements in reading might account for the effects of word characteristics on both the direction and length of refixation saccades. Perhaps an alternative approach would be to suggest that linguistic information might influence the activity of the fixated word within a salience map. Such an explanation could correspond to the salience based suggestion made in Section 6.1.3 to explain effects of orthography on first fixation positions.

According to the salience based account described in Section 6.1.3, the linguistic module provides lexical and sub-lexical activation equally to each letter within a particular non-fixated word, limited by processing load. This same mechanism might be used to influence the programming of refixation saccades. That is, although lexical and sub-lexical activation is allocated equally to letters within non-fixated words, it might be allocated to individual letters or letter sequences within words. If the fixated word had an orthographically irregular beginning the linguistic module would induce greater activation in the salience map at this location and so refixations would be more likely to be directed to the word beginning (generally, to the left of the initial fixation). Furthermore, if the word was difficult to process then letters nearer to fixation would be more activated than letters further away due to the limited processing resources. Hence refixation saccades would be shorter because there would be higher salience nearer to the fixation position. Such an account might explain how orthography, and other factors such as morphology, might influence the direction and length of refixation saccades. Therefore, processing of orthography, independent of processing load, might influence programming of inter-word saccades, and general linguistic processing, limited by processing load, might influence programming of intra-word saccades.

6.3: Parafoveal-on-foveal Effects

Section 6.1.1 shows that the orthographic characteristics of words are preprocessed such that they influence saccade computation on the fixation prior to fixating the word. As explained in Section 1.5, these experiments provide a good test of parafoveal-on-foveal effects because the landing position results clearly show that the differences in orthography were processed on the previous fixation. According to parallel processing accounts (Engbert & Kliegl, 2001; Engbert, et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Reilly & Radach, 2003; Schiepers, 1980) the characteristics of a non-foveal word can influence prior fixation durations or probabilities because multiple words can be processed in parallel. In contrast, serial attention shift accounts suggest that the characteristics of words can not influence prior fixation patterns (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press).

6.3.1: Summary of results

Parafoveal-on-foveal effects might occur in the form of influencing prior fixation durations, or influencing the probability of skipping or refixating words prior to the critical word. As discussed above, Experiment 1 showed that word n-1 was more likely to be skipped, and Experiment 6 showed that word n-1 was numerically more likely to be refixated, when the critical string was orthographically irregular compared to when it was regular. However, there were no consistent differences in fixation probabilities prior to fixating the critical string across the experiments. In contrast to previous studies showing effects of orthographic preprocessing on prior fixation durations (Inhoff, Starr, et al., 2000; Rayner, 1975; Underwood et al., 2000; Vitu et al., in press; Starr & Inhoff, in press), Experiments 1, 4, 5, and 6 showed no evidence that the orthographic characteristics of words influence the duration of prior fixations. Experiment 7 did show that fixation durations were longer prior to fixating misspelled compared to correctly spelled critical strings when saccades were launched from three or less characters from the beginning of the critical string. However, the fact that this effect was isolated to such near launch sites suggests that it might be due to oculomotor error, as discussed in Sections 1.5 and 5.2.3. Furthermore, although previous studies have reported that lexical preprocessing can influence prior fixations (Inhoff, Radach et al., 2000; Kennedy, 1998, 2000b; Kennedy et al., in press; Kennedy et al., 2002; Pynte et al., in press; Lavigne et al., 2000; Murray, 1998; Murray & Rowan, 1998), Experiments 2 and 3 showed no evidence of such effects.

Therefore the results strongly suggest that although parafoveal-on-foveal effects do seem to arise under some conditions (for example, due to oculomotor error), the effects are not consistent or robust. The absence of effects on prior durations is particularly striking for the four experiments (Experiments 1, 4, 5, and 6) which show that orthography influences fixation positions. These results suggest that parafoveal-on-foveal effects on prior fixation durations did not occur even though the orthographic characteristics of the words were shown to be processed on the prior fixation.

6.3.2: Implications for models of eye movements in reading

The results support models of eye movements in reading in which words are processed serially such that the characteristics of a word can not influence prior fixation patterns (Morrison, 1984; Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press). According to these accounts, it is possible that the characteristics of a word might influence the duration of fixations at the very end of the previous word if saccades intended for the critical word land there due to oculomotor error. However the results question accounts suggesting that multiple words can be processed in parallel such that processing of a word can influence eye movement behaviour on the previous word (Engbert & Kliegl, 2001; Engbert et al., 2002; Inhoff, Radach et al., 2000; Kennedy, 2000a; Reilly & Radach, 2003; Schiepers, 1980). Parallel processing accounts should at least explain why parafoveal-on-foveal effects do not always hold, especially when the manipulations of non-foveal word characteristics are very strong as in the experiments presented here.

Perhaps the most interesting aspect of the absence of parafoveal-on-foveal effects is that the landing position results clearly show that non-foveal orthography was preprocessed before the words were fixated. That is, the non-foveal orthographic characteristics were preprocessed such that they influenced where, but not when, the eyes moved. These findings are consistent with those discussed in Section 1.1.4 showing that different processes determine when and where the eyes move.

There are two possible explanations for the presence of landing position, but absence of parafoveal-on-foveal, effects. First, preprocessing might influence when and where the eyes move, but this information might be utilised at different times. Non-foveal words might be preprocessed after attention has shifted to word n+1 and after an eye movement has been programmed to word n+1. The preprocessed information could be integrated across saccades to facilitate processing on the subsequent fixation, but because the saccade has all ready been programmed the preprocessed information could not influence the duration of the current fixation. However, such preprocessing could still influence programming of the saccade amplitude after the decision to programme an eye movement had been made (Becker & Jürgens, 1979). However, if the same types of preprocessing could influence both when and where processes then this would predict that an influence of orthography on landing positions should be accompanied by an influence of orthography on preview benefit. That is, preprocessing would influence both where the eyes moved and when the eyes moved on the subsequent fixation. However, the reduced data set of 20 participants in Experiment 7 (Section 5.3) does not show such a pattern of effects. For this data set the measures of preview benefit showed no clear evidence of orthographic preprocessing, whilst the effects of orthography on saccade programming remained strong.

The evidence from Experiment 7 suggests that a different account is needed to explain why non-foveal preprocessing can be shown to influence saccade programming, but not prior fixation durations or preview benefit. The evidence suggests that even if the when and where systems have been shown to use the same types of non-foveal (e.g. orthographic) information, they might do this quite independently and with quite different mechanisms. For example, preprocessing of orthography might be limited by processing resources for the when system, but not for the where system. However, it is important to point out that discussion of the "where" system in this section has been in relation to saccade programming to a particular word. It is possible that the non-foveal information that influences which words are fixated could be processed in a similar way to that which determines preview benefit.

For example, both word skipping and preview benefits might be limited by processing resources, perhaps because they might both depend on large discrete shifts in attention.

To summarise, the experiments in this thesis provide no consistent evidence for parafoveal-on-foveal effects. These results have two important implications. First, parallel processing models of eye movements in reading must explain why parafoveal-on-foveal effects do not always occur. Secondly, the processes that determine when the eyes move and programming of where to move the eyes to the following word are quite independent.

6.4: General Phenomena

The experiments presented in this thesis provided an opportunity to evaluate a number of general phenomena investigated in previous studies. The results confirm a number of classic results reported in many earlier studies. However the experiments also question earlier findings including those for reading of upper compared to lower case text, the effects of foveal load on non-foveal processing, the effects of fixation position on single fixation durations and the effects of prior fixation durations on saccade targeting accuracy.

6.4.1: Summary of results

The experiments demonstrated a range of classic results which have been shown in many previous studies and which were described in Section 1.2.1. All of the experiments show that most first fixations on words land on the preferred viewing position, which is just left of the word centre (Dunn-Rankin, 1978; McConkie et al., 1988; Rayner, 1979). The preferred viewing position indicates that word length is an important factor in determining where words are first fixated. The experiments also show that fixations land nearer to the beginning of words for saccades launched from more distant launch sites, consistent with the range effect (Hyönä, 1995; McConkie et al., 1994; McConkie et al., 1988; Radach & Kempe, 1993; Radach & McConkie, 1998; Rayner et al., 1996). Also in support of previous studies (Balota & Rayner, 1983; Inhoff, 1989a; McClelland & O'Regan, 1981; McConkie & Zola, 1979; Rayner et al., 1980; Rayner et al., 1982), Experiment 7 showed that the orthographic characteristics of words can be preprocessed and integrated across fixations such that this facilitates processing (produces preview benefit) once the word is fixated. However, in contrast to previous studies (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens et al., 1999) foveal processing difficulty did not modulate the amount of non-foveal preview benefit.

A number of other general phenomena were investigated in Chapter 4. Experiment 5 showed that there was little difference in eye movement measures for the reading of lower compared to upper case text (Section 4.3). These results contrast with those of Tinker and Paterson (1939). It was suggested (Section 4.3.2) that Tinker and Paterson may have found different results because they did not control for the size of the text. The similar reading behaviour for lower and upper case text shown in Experiment 5 suggests that very similar processes are used for reading them, for example, abstract processing of non-foveal text. The data from Experiments 4 and 5 were also used to investigate other oculomotor phenomena (Section 4.4). In contrast to isolated word recognition studies (O'Regan & Jacobs, 1992; O'Regan et al., 1984) and in line with recent reading studies (O'Regan et al. 1994; Radach & Heller, 2000; Vitu et al., 2001), single fixation durations were shown to be longer for fixations near the word centre than fixations towards the end of words. The orthographic regularity of the words influenced fixation durations for all of the possible fixation positions on the words. It is unclear why such an inverted optimal viewing position effect occurs, one possible explanation is that fixations towards the end of the words are more likely to be due to oculomotor error, they may have been targeted to different words. Other analyses suggested that, in contrast to studies showing that longer prior fixation durations produce more accurate saccade targeting to words (Beauvillain & Doré, 1995; McConkie et al., 1994; McConkie et al., 1988), and in support of recent studies (Radach & Heller, 2000; Radach & McConkie, 1998), prior fixation duration did not influence saccade targeting accuracy. In addition, further analyses suggested that relationships between prior fixation duration and subsequent saccade lengths might be confounded by differences in launch site producing differences in fixation duration. These results have important implications for models of eye movements in reading.

6.4.2: Implications for models of eye movements in reading

The results have important implications for models of eye movements in reading which suggest that non-foveal processing is limited by foveal load; that fixation durations are shorter when positioned at the word centre; or that long prior fixation durations improve saccade targeting accuracy. Experiment 7 did not show any effect of foveal load on the amount of preview benefit, even when only cases which provided the best conditions for such an effect were included in the analysis. The issue has important architectural implications for models of reading. In the E-Z reader model (Rayner, Reichle et al., 1998; Reichle et al., 1998; Reichle et al., 1999, in press) the modulation of preview benefit by foveal load is explained by the de-coupling of eye movements and attention. If such a mechanism is not required then simpler accounts, such as a direct coupling between eye movements and attention, might actually be more accurate. Due to the importance of this issue, further studies must be undertaken to determine if the influence of foveal load on non-foveal preprocessing is reliable, or whether it is specific to any particular kinds of non-foveal preprocessing.

Models of eye movements in reading in which eccentricity modulates word processing speed (Engbert et al., 2002; Reichle et al., 1999, in press; Reilly & Radach, 2003; Yang & McConkie, 2001) or simply fixation durations (O'Regan, 1990) might predict that fixation durations should be shorter when located at the word centre. These predictions are opposite to the finding of an inverted optimal viewing position, such that fixations nearer the word centre are longer, rather than shorter, than those nearer the ends of words. However, it is unclear (see Vitu et al., 2001) what determines the inverted optimal viewing position effect and therefore how models of eye movements in reading might explain it.

Models of eye movements in reading which adopt all of McConkie et al.'s (1988) principles of saccade targeting (e.g. Reichle et al., in press) predict an effect of prior fixation duration on saccade targeting accuracy. However, analyses presented here show no evidence for this, which at least suggests that the effect is not robust. Therefore the models might be more cautious about making such a prediction until the relationship between prior fixation duration and saccade targeting accuracy has been studied more extensively.

6.5: Conclusions

6.5.1: Theoretical implications and suggestions

Sections 6.1.3 and 6.2.2 outlined an alternative explanation to account for the effects of orthography on first fixation and refixation saccade programming. This account of where the eyes move in reading is largely based on ideas originally proposed by the attraction hypotheses (Beauvillain & Doré, 1997; Beauvillain et al., 1996; Hyönä, 1993b; McConkie, 1979), the processing difficulty hypothesis (Hyönä & Pollatsek, 1998, 2000), salience map based accounts of saccade programming (e.g. Clark, 1999; Findlay & Walker, 1999; Henderson, 1992) and the Glenmore model (Radach et al., in press; Reilly & Radach, 2003).

The account is based on four important assumptions. First, saccades are directed to the point of maximum salience in a letter based salience map. The levels of salience reflect spatially localised processing activity at both a visual and abstract linguistic processing level. Activation in the salience map is limited by eccentricity and is influenced by the linguistic module. Secondly, visual influences on the salience map ensure that word length and launch site affect the point of maximum salience and therefore influence first fixation and refixation positions (as explained in Section 1.3.1). Thirdly, the linguistic module processes lexical and sub-lexical information for both fixated and non-fixated words in a resource limited manner. Fourthly, the linguistic module processes letter sequence familiarity for non-fixated words limited only by acuity and processes such as lateral masking.

According to the account, the linguistic module uses the lexical and sub-lexical information to influence activation of letters within the fixated word. The same information also influences the activation of non-fixated words such that each letter within a non-fixated word receives the same level of lexical and sub-lexical activation. Therefore the account predicts that sub-lexical and lexical properties influence which word will be fixated next and programming of refixation saccades within the fixated word. Refixations are directed to parts of the fixated word that are more difficult to process. Furthermore, with high foveal processing load, activity is generally highest nearer fixation and so refixation saccades are shorter and words are less likely to be skipped. The linguistic module also uses letter sequence familiarity information to influence activation of letters within non-fixated words, regardless of processing load. Consequently, orthographic regularity weights the word length and launch site based saccade programme such that the preferred viewing position is slightly shifted in the direction of the irregularity. Importantly, such preprocessing of orthography is independent of processing load and any processes influencing when the eyes move (as discussed in Section 6.3.2).

Most models of eye movements in reading do not attempt to explain how orthographic factors might influence where words are first fixated and refixated (O'Regan, 1990; Reichle et al., 1999, in press; Reilly & O'Regan, 1998; Reilly & Radach, 2003; Suppes, 1990). However, as explained in Section 1.3.4, until recently there were only three studies undertaken in languages other than English (Hyönä, 1995; Radach et al., in press; Vonk et al., 2000) to suggest that the orthography of word initial letters influences where words are first fixated in reading. The experiments reported in this thesis provide further strong evidence for orthographic influences on saccade programming. Therefore any full account of eye movements in reading must now account for these effects. The architecture described above provides a possible explanation for the findings, which could be incorporated into more comprehensive accounts of both when and where the eyes move in reading.

6.5.2: Final conclusions

Overall, the experiments presented in this thesis clearly show that non-foveal preprocessing of letter sequence familiarity (not lexical preprocessing) can influence saccade programming in the reading of English sentences. Importantly, the influence of orthography on saccade programming does not require the visually distinctive letter features provided by lower case text, and the effects are independent of general processing load. Furthermore the orthography, or difficulty, of words also influences the direction and length of refixation saccades. In addition, although non-foveal characteristics influence saccade programming on the previous fixation, the same features do not reliably influence the duration of those fixations.

Most importantly, the experiments provide robust evidence that orthography influences first fixation positions on words. Therefore models of eye movements in reading should now incorporate mechanisms to explain these effects. Such a mechanism might use non-foveal preprocessing of orthography independent of processing load in order to modulate the word length and launch site based saccade computation.

References

Altarriba, J., Kambe, G., Pollatsek, A., & Rayner, K. (2001). Semantic codes are not used in integrating information across eye fixations in reading: Evidence from fluent Spanish-English bilinguals. *Perception & Psychophysics, 63,* 875-890.

Altarriba, J., Kroll, J.F., Sholl, A., & Rayner, K. (1996). The influence of lexical and conceptual constraints on reading mixed-language sentences: Evidence from eye fixations and naming times. *Memory & Cognition, 24,* 477-492.

Andriessen, J.J., & de Voogd, A.H. (1973). Analysis of eye movement patterns in silent reading. *IPO Annual Progress Report, 8,* 29-34.

Andrews, S., Miller, B., & Rayner, K. (in press). Eye movements and morphological segmentation of compound words: There is a mouse in mousetrap. *European Journal of Cognitive Psychology*

Appelman, I.B., & Mayzner, M.S. (1981). The letter-frequency effect and the generality of familiarity effects on perception. *Perception & Psychophysics, 30,* 436-446.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). The CELEX Lexical Database. [CD-ROM]. Philadelphia: Linguistic Data Consortium, University of Pennsylvania.

Balota , D.A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology, 17,* 364-390.

Balota, D.A., & Rayner, K. (1983). Parafoveal visual information and semantic contextual constraints. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 726-738.

Balota, D.A., & Rayner, K. (1991). Parafoveal visual information and semantic contextual constraints. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 726-738.

Bassou, L., Pugh, A.K., & Granié, M. (1993). Binocular vision in reading: A study of the eye movements of ten year old children. In G. d'Ydewalle, & J. Van Rensbergen, (Eds.), *Perception and Cognition: Advances in Eye Movement Research* (pp. 297-308.) Amsterdam: Elsevier.

Beauvillain, C. (1996). The integration of morphological and whole-word integration during eye fixations of prefixed and suffixed words. *Journal of Memory and Language, 35,* 801-820.

Beauvillain, C., & Doré, K. (1995). Effect of luminance and linguistic information on the center of gravity of words. In J.M. Findlay, R. Walker, & R.W. Kentridge (Eds.), *Eye Movement Research: Mechanisms, processes and applications* (pp. 393-403). Amsterdam: North Holland.

Beauvillain, C., & Doré, K. (1998). Orthographic codes are used in integrating information from the parafovea by the saccadic computation system. *Vision Research, 38,* 115-123.

Beauvillain, C., Doré, K., & Baudouin, V. (1996). The "Centre of gravity" of words: Evidence for an effect of word-initial letters. *Vision Research, 36,* 589-603.

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research, 19,* 967-983.

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structure: Evidence from eye movements when reading short and long Finnish compounds. *Journal of Memory and Language, 48,* 615-634.

Binder, K.S., Pollatsek, A., & Rayner, K. (1999). Extraction of information to the left of the fixated word in reading. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1162-1172.

Blanchard, H.E., Pollatsek, A., & Rayner, K. (1989). The acquisition of parafoveal word information in reading. *Perception & Psychophysics, 46,* 85-94.

Bouma, H., & de Voogd, A.H. (1974). On the control of eye saccades in reading. *Vision Research, 14,* 273-284.

Brysbaert, M., & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Eye Guidance in Reading and Scene Perception* (pp. 125-148). Oxford, UK: Elsevier.

Buswell, G.T. (1937). *How adults read.* Chicago: University of Chicago Press.

Carpenter, P.A., & Just, M.A. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 275-307). New York: Academic Press.

Clark, J.J. (1999). Spatial attention and latencies of saccadic eye movements. *Vision Research, 39,* 585-602.

Coëffé, C., & O'Regan, J.K. (1987). Reducing the influence of non-target stimuli on saccade accuracy: Predictability and latency effects. *Vision Research, 27,* 227-240.

Coren, S., & Hoenig, P. (1972). Effect of non-target stimuli upon length of voluntary saccades. *Perception and Motor Skills, 34,* 499-508.

Cornelissen, P, Munro, N., Fowler, S., & Stein, J. (1993). The stability of binocular fixation during reading in adults and children. *Developmental Medicine and Child Neurology, 35,* 777-787.

Daneman, M., Reingold, E. M., & Davidson, M. (1995). Time course of phonological activation during reading: Evidence form eye fixations. *Journal Of Experimental Psychology: Learning, Memory and Cognition, 21,* 884-898.

Deubel, H., & Schneider, W.X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36,* 1827-1837.

Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2000). Early morphological effects in word recognition in Hebrew: Evidence from parafoveal preview benefit. *Language and Cognitive Processes, 15,* 487-506.

Deutsch, A., & Rayner, K. (1999). Initial fixation location effects in reading Hebrew words. *Language and Cognitive Processes, 14,* 393-421.

Doré, K., & Beauvillain, C. (1997). Latency dependence of word-initial letter integration by the saccadic system. *Perception & Psychophysics, 59,* 523-533.

Doré, K., & Beauvillain, C. (1999). Relationship between visual attention and saccades target selection in reading. In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research. Physiological and psychological aspects* (pp. 375-378). New York: Kluwer Academic, Plenum.

Doré-Mazars, K., Pouget, P., & Beauvillain, C. (2002). Evidence for a dynamic coupling between selection for perception and action. [Poster] *Movement, Action and Visual Selection, Dourdan.*

Drieghe, D., Brysbaert, M., Desmet, T., & De Baecke, C. (in press). Word skipping in reading: On the interplay of linguistic and visual factors. *European Journal of Cognitive Psychology*

Ducrot, S., & Pynte, J. (2002). What determines the eyes' landing position in words? *Perception & Psychophysics, 64,* 1130-1144.

Dunn-Rankin, P. (1978). The visual characteristics of words. *Scientific American, 238,* 122-130.

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning and Verbal Behaviour, 20,* 641-655.

Engbert, R., & Kliegl, R. (2001). Mathematical models of eye movements in reading: a possible role for autonomous saccades. *Biological Cybernetics, 85,* 77-87.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42,* 621-636.

Epelboim, J., Booth, J.R., Ashkenazy, R., Taleghani, A., & Steinman, R.M. (1997). Fillers and spaces in text: The importance of word recognition during reading. *Vision Research, 37,* 2899-2914.

Epelboim, J., Booth, J.R., & Steinman, R.M. (1994). Reading unspaced text: Implications for theories of reading eye movements. *Vision Research, 34,* 1735-1766.

Epelboim, J., Booth, J.R., & Steinman, R.M. (1996). Much ado about nothing: The place of space in text. *Vision Research, 36,* 465-470.

Everatt, J., Bradshaw, M. F., & Hibbard, P. B. (1998). Individual differences in reading and eye movement control. In G. Underwood (Ed.), *Eye Guidance in reading and scene perception* (pp. 223-242). Oxford, UK: Elsevier.

Everatt, J., & Underwood, G. (1992). Parafoveal guidance and priming effects during reading: A special case of the mind being ahead of the eyes. *Consciousness and Cognition, 1,* 186-197.

Farid, M., & Grainger, J. (1996). How initial fixation position influences visual word recognition: A comparison of French and Arabic. *Brain and Language, 53,* 351-368.

Findlay, J.M. (1981a). Local and global influences on saccadic eye movements. In D.F. Fisher, R.A. Monty, & J.W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 171-179). NJ: Lawrence Erlbaum.

Findlay, J.M. (1981b). Spatial and temporal factors in the predictive generation of saccadic eye movements. *Vision Research, 21,* 347-354.

Findlay, J.M. (1982). Global visual processes for saccadic eye movements. *Vision Research, 22,* 1033-1045.

Findlay, J.M. & Harris, L.R. (1984). Small saccades to double stepped targets moving in two dimensions. In A.G. Gale & F. Johnson (Eds.), *Theoretical and Applied Aspects of Eye Movement Research* (pp. 71-78). Amsterdam: Elsevier.

Findlay, J.M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioural and Brain Sciences, 22*, 661-674.

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the Analysis of Structurally Ambiguous Sentences. *Cognitive Psychology, 14,* 178-210.

Gautier, V., O'Regan, J.K., & Le Gargasson, J.F. (2000). "The-skipping" revisited in French: Programming saccades to skip the article "les". *Vision Research, 40,* 2517-2531.

Grainger, J., O'Regan, J.K., Jacobs, A.M., & Segui, J. (1992). Neighbourhood frequency effects and letter visibility in visual word recognition. *Perception & Psychophysics, 51,* 49-56.

Heller, D., & Radach, R. (1995). Binocular coordination of eye movements in complex visual tasks. *Perception, 24,* 72 (Supplement).

Heller, D., & Radach, R. (1999). Eye movements in reading: Are two eyes better than one? In W. Becker, H. Deubel, & T. Mergner (Eds.), *Current oculomotor research. Physiological and psychological aspects* (pp. 341-348). New York: Kluwer Academic, Plenum.

Henderson, J.M. (1992). Visual attention and eye movement control during reading and picture viewing. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 260-283). New York: Springer-Valag.

Henderson, J.M., Dixon, P., Peterson, A., Twilley, L.C., & Ferreira, F. (1995). Evidence for the use of phonological representations during transaccadic word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 82-97.

Henderson, J.M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory and Cognition, 16,* 417-429.

Henderson, J.M., & Ferreira, F. (1993). Eye movement control during reading: Fixation measures reflect foveal but not parafoveal processing difficulty. *Canadian Journal of Experimental Psychology, 47,* 201-221.

Hendriks, A.W. (1996). Vergence eye movements during fixations in reading. *Acta Psychologica, 92,* 131-151.

Hill, R. L., & Murray, W. S. (2000). Commas and spaces: Effects of punctuation on eye movements and sentence parsing. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), Reading as a perceptual process (pp. 565-589). Oxford, UK: Elsevier.

Hochberg, J. (1975). On the control of saccades in reading. *Vision Research, 15,* 620.

Hochberg, J. (1976). Toward a speech-plan eye movement model of reading. In R.A. Monty & J.W. Senders (Eds.), *Eye movements and psychological processes* (pp. 373-395). NJ: Lawrence Erlbaum Associates.

Hoffman, J.E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics, 57,* 787-795.

Hogaboam, T.W. (1983). Reading patterns in eye movements. In K. Rayner (Ed.), *Eye movements in reading* (pp. 309-332). New York: Academic Press.

Huey, E.B. (1908). *The Psychology and Pedagogy of Reading.* New York: MacMillan.

Hyönä, J. (1993a). Effects of thematic and lexical priming on readers' eye movements. *Scandinavian Journal of Psychology, 34,* 293-304.

Hyönä, J. (1993b). *Eye movements during reading and discourse processing.* [Psychological Research Rep. No. 65]. Turku, Finland: University of Turku.

Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 68-81.

Hyönä, J., & Bertram, R. (in press a). Do frequency characteristics of non-fixated words influence the processing of fixated words during reading? *European Journal of Cognitive Psychology*

Hyönä, J., & Bertram, R. (in press b). Future challenges to E-Z reader: Effects of OVP and morphology on processing of long and short compound words. *Behavioural and Brain Sciences*

Hyönä J., Niemi, P., & Underwood, G. (1989). Reading long words embedded in sentences: Informativeness of word halves affects eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 142-152.

Hyönä, J., & Pollatsek, A. (1998). Reading Finnish compound words: Eye fixations are affected by component morphemes. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1612-1627.

Hyönä, J., & Pollatsek, A. (2000). Processing of Finnish compound words in reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 65-87). Oxford, UK: Elsevier.

Ikeda, M., & Saida, S. (1978). Span of recognition in reading. *Vision Research, 18,* 83-88.

Inhoff, A.W. (1982). Parafoveal word perception: A further case against semantic preprocessing. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 137-145.

Inhoff, A.W. (1989a). Lexical access during eye fixations in reading: Are word access codes used to integrate lexical information across interword fixations. *Journal of Memory and Language, 28,* 444-461.

Inhoff, A.W. (1989b). Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 544-555.

Inhoff, A.W. (1990). Integrating information across eye fixations in reading: The role of letter and word units. *Acta Psychologica, 73,* 281-297.

Inhoff, A.W., Briihl, D., & Schwartz, J. (1996). Compound word effects differ in reading, on-line naming and delayed naming tasks. *Memory and Cognition, 24,* 466-476.

Inhoff, A.W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 20-24.

Inhoff, A.W., Pollatsek, A., Posner, M.I., & Rayner, K. (1989). Covert attention and eye movements during reading. *Quarterly Journal of Experimental Psychology, 41A,* 63-89.

Inhoff, A.W., Radach, R., Eiter, B.M., & Juhasz, B. (2003). Distinct subsystems for the parafoveal processing of spatial and linguistic information during eye fixations in reading. *Quarterly Journal of Experimental Psychology, 56A,* 803-827.

Inhoff, A. W., Radach, R., Starr, M., & Greenberg, S. (2000) Allocation of visuo-spatial attention and saccade programming during reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 221-246). Oxford, UK: Elsevier.

Inhoff, A.W., & Rayner, K. (1980). Parafoveal word perception: A case against semantic preprocessing. *Perception & Psychophysics, 27,* 457-464.

Inhoff, A.W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40,* 431-439.

Inhoff, A.W., Starr, M., & Shindler, K.L. (2000). Is the processing of words during eye fixations in reading strictly serial? *Perception & Psychophysics, 62,* 1474-1484.

Inhoff, A.W., & Topolski, R. (1994). Use of phonological codes during eye fixations in reading and on-line and delayed naming tasks. *Journal of Memory and Language, 33,* 689-713.

Inhoff, A. W., Topolski, R., & Wang, J. (1992). Saccade programming during short duration fixations: An examination of copytyping, letter detection, and reading. *Acta Psychologica, 81,* 1-21.

Jacobson, J.Z., & Dodwell, P.C. (1979). Saccadic eye movements during reading. *Brain and Language, 8,* 303-314.

Just, M.A., & Carpenter, P.A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87,* 329-354.

Kajii, N., Nazir, T.A., & Osaka, N. (2001). Eye movement control in reading unspaced text: The case of the Japanese script. *Vision Research, 41,* 253-2510.

Kajii, N., & Osaka, N. (2000). Optimal viewing position in vertically and horizontally presented Japanese words. *Perception & Psychophysics, 62,* 1634-1644.

Kapoula, Z. (1985). Evidence for a range effect in the saccadic system. *Vision Research, 25,* 1155-1157.

Kapoula, Z., & Robinson, D.A. (1986). Saccadic undershoot is not inevitable: Saccades can be accurate. *Vision Research, 26,* 735-743.

Kennedy, A. (1998). The influence of parafoveal words on foveal inspection time: Evidence for a processing trade off. In G. Underwood (Ed.), *Eye Guidance in reading and scene perception* (pp. 149-179). Oxford, UK: Elsevier.

Kennedy, A. (2000a). Attention allocation in reading: Sequential or parallel? In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 193-220). Oxford, UK: Elsevier.

Kennedy, A. (2000b). Parafoveal processing in word recognition. *Quarterly Journal of Experimental Psychology, 53A,* 429-455.

Kennedy, A., Murray, W.S., & Boissiere, C. (in press). Parafoveal Pragmatics Revisited. *European Journal of Cognitive Psychology*

Kennedy, A., Pynte, J., & Ducrot, S. (2002). Parafoveal-on-foveal interactions in word recognition. *Quarterly Journal of Experimental Psychology, 55A,* 1307-1337.

Kennison, S.M., & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning Memory and Cognition, 21,* 68-81.

Kleigl, R., Olson, R.K., & Davidson, B.J. (1982). Regression analyses as a tool for studying reading processes: Comment on Just and Carpenter's eye fixation theory. *Memory and Cognition, 10,* 287-296.

Kolers, P.A. (1976). Buswell's discoveries. In: R.A. Monty & J.W. Senders (Eds.), *Eye movements and psychological processes* (pp. 373-395). NJ: Lawrence Erlbaum Associates.

Kowler, E., Anderson,E., Dosher, B., & Blaser, E. (1995).The role of attention in the programming of saccades. *Vision Research, 35,* 1897-1916.

Laberge, D., & Brown, V. (1989). Theory of attentional operation in shape identification. *Psychological Review, 96,* 101-124.

Lavigne, F., Vitu, F., & d'Ydewalle, G. (2000). The influence of semantic context on initial eye landing sites in words. *Acta Psychologica, 104,* 191-214.

Legge, G.E., Hooven, T.A., Klitz, T.S., Mansfield, J.S., & Tjan, B.S. (2002). Mr. Chips 2002: new insights from an ideal-observer model of reading. *Vision Research, 42,* 2219-2234.

Legge, G.E., Klitz, T.S., & Tjan, B.S. (1997). Mr. Chips: An ideal-observer model of reading. *Psychological Review, 104,* 524-553.

Lima, S.D. (1987). Morphological analysis in sentence reading. *Journal of Memory And Language, 26,* 84-99.

Lima, S.D., & Inhoff, A.W. (1985). Lexical access during eye fixations in reading: Effects of word initial letter sequence. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 272-285.

Liu, W., Inhoff, A.W., Ye, Y., & Wu, C. (2002). Use of parafoveally visible characters during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1213-1227.

Liversedge, S.P., & Underwood, G. (1998). Foveal processing load and landing position effects in reading. In G. Underwood (Ed.), *Eye Guidance in reading and scene perception* (pp. 201-221). Oxford, UK: Elsevier.

McClelland, J.L., & O'Regan, J.K. (1981). Expectations increase the benefit derived from parafoveal visual information in reading words aloud. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 634-644.

McConkie, G. W. (1979). On the role and control of eye movements in reading. In P.A. Kolers, M.E. Wrolstad, & H. Bouma (Eds.), *Processing of visible language* (pp. 37-48). New York: Plenum.

McConkie, G.W., Kerr, P.W., & Dyre, B.P. (1994). What are "normal" eye movements during reading: Toward a mathematical description. In J. Ygge, & G. Lennerstrand (Eds.), *Eye movements in reading* (pp. 315-328). Oxford, UK: Pergamon Press.

McConkie, G.W., Kerr, P.W., Reddix, M.D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28,* 1107-1118.

McConkie, G.W., Kerr, P.W., Reddix, M.D., Zola, D., & Jacobs, A.M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics, 46,* 245-253.

McConkie, G.W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17,* 578-586.

McConkie, G.W., & Rayner, K. (1976a). Asymmetry of the perceptual span in reading. *Bulletin of the psychonomic society, 8,* 365-368.

McConkie, G.W., & Rayner, K. (1976b). Identifying the span of the effective stimulus of reading: Literature review and theories of reading. In H. Singer & R.B.

Ruddell (Eds.), *Theoretical models and processes in reading* (pp. 137-162). Newark, DE: Internation Reading Association.

McConkie, G.W., Underwood, N.R., Zola, D., & Wolverton, G.S. (1985). Some temporal characteristics of processing during reading. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 168-186.

McConkie, G.W., & Zola, D. (1979). Is visual information integrated across successive fixations in reading. *Perception & Psychophysics, 25,* 221-224.

McConkie, G.W., & Zola, D. (1984). Eye movement control during reading: The effect of word units. In W. Prinz & A.F. Senders (Eds.), *Cognition and motor processes* (pp. 63-74). Berlin: Springer.

Morris, R.K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 268-281.

Morrison, R.E. (1983). Retinal image size and the perceptual span in reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 31-40). New York: Academic Press.

Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 667-682.

Morrison, R.E., & Inhoff, A.W. (1981). Visual factors and eye movements in reading. *Visible Language, 15,* 129-146.

Morrison, R.E., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Perception & Psychophysics, 30,* 395-396.

Murray, W.S. (1998). Parafoveal pragmatics. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 181-200). Oxford, England: Elsevier.

Murray, W.S., & Rowan, M. (1998). Early, mandatory, pragmatic processing. *Journal of Psycholinguistic Research, 27,* 1-22.

O'Regan, K. (1979). Saccade size control in reading: Evidence for the linguistic control hypothesis. *Perception and Psychophysics, 25,* 501-509.

O'Regan, K. (1980). The control of saccade size and fixation duration in reading: The limits of linguistic control. *Perception and Psychophysics, 28,* 112-117.

O'Regan, K. (1981). The convenient viewing position hypothesis. In D.F. Fisher, R.A. Monty, & J.W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp.289-298). Hillsdale, NJ: Erlbaum.

O'Regan, K. (1983). Elementary perceptual and eye movement control processes in reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 121-140). New York: Academic Press.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395-453). Amsterdam: Elsevier.

O'Regan, J.K., & Jacobs, A.M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 185-197.

O'Regan, J.K., & Lévy-Schoen, A. (1987). Eye-movement strategy and tactics in word recognition and reading. In M. Coltheart (Ed.), *Attention and performance: Vol. XII. The psychology of reading* (pp. 363-383). Hillsdale, NJ: Erlbaum.

O'Regan, J.K., Lévy-Schoen, A., & Jacobs, A.M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception & Psychophysics, 34,* 457-464.

O'Regan, J.K., Lévy-Schoen, A., Pynte, J., & Brugaillère, B. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 250-257.

O'Regan, J.K., Vitu, F., Radach, R., & Kerr, P.W. (1994). Effects of local processing and oculomotor factors in eye movement guidance in reading. In J. Ygge, & G. Lennerstrand (Eds). *Eye movements in reading* (pp. 329-348). Oxford, UK: Pergamon Press.

Osaka, N. (1987). Effect of peripheral visual field size upon eye movements during Japanese text processing. In J.K. O'Regan & A. Lévy-Schoen (Eds.), *Eye movements: From physiology to cognition* (pp. 421-429). Amsterdam: Elsevier Science, North Holland.

Osaka, N. (1993). Asymmetry of the effective visual field in vertical reading as measured with a moving window. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and Cognition: Advances in eye movement research* (pp. 275-283). Amsterdam: North Holland.

Paterson, D.G., & Tinker, M.A. (1946). Readability of newspaper headlines printed in capitals and in lower case. *Journal of Applied Psychology, 30,* 161-168.

Paterson, D.G., & Tinker, M.A. (1947). The effect of typography upon the perceptual span in reading. *American Journal of Psychology, 60,* 388-396.

Pollatsek, A., Bolozky, S. Well, A.D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language, 14,* 174-180.

Pollatsek, A., Lesch, M., Morris, R.K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 148-162.

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: the role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 817-833.

Pollatsek, A., & Rayner, K. (1990). Eye movements and lexical access in reading. In D.A. Balota, G.B. Flores d'Arcais & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 143-164). Hillsdale, NJ: Erlbaum.

Pollatsek, A., Rayner, K., & Balota, D.A. (1986). Inferences about eye movement control from the perceptual span in reading. *Perception & Psychophysics, 40,* 123-130.

Pollatsek, A., Tan, L.H., & Rayner, K. (2000). The role of phonological codes in integrating information across saccadic eye movements in Chinese character identification. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 607-633.

Pynte, J. (1996). Lexical control of within word eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 958-969.

Pynte, J. (2000). Words likely to generate many lexical candidates are granted an advantage: Evidence from within-word eye movements. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 47-64). Oxford, UK: Elsevier.

Pynte, J., Kennedy, A., & Ducrot, S. (in press). Error detection in the parafovea. *European Journal of Cognitive Psychology*

Pynte, J., Kennedy, A., & Murray, W.S. (1991). Within-word inspection strategies in continuous reading: Time course of perceptual, lexical and contextual processes. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 458-470.

Radach, R., & Heller, D. (2000). Relations between spatial and temporal aspects of eye movement control. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 165-191). Netherlands: Elsevier North Holland.

Radach, R., Heller, D., Wiebories, P., & Jaschinski, W. (1996). Binocular co-ordination, fixation disparity and ocular dominance. *Perception, 25,* 87 [Supplement].

Radach, R., Inhoff, A., & Heller, D. (in press). Orthographic regularity gradually modulates saccade amplitudes in reading. *European Journal of Cognitive Psychology*

Radach, R., & Kempe, V. (1993). An individual analysis of initial fixation positions in reading. In G. d'Ydewalle, & J. Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 213-226). Amsterdam: Elsevier.

Radach, R., Krummenacher, J, Heller, D., & Hofmeister, J. (1995). Individual eye movement patterns in word recognition: Perceptual and linguistic factors. In J.M. Findlay, R. Walker, & R.W. Kentridge (Eds.), *Eye Movement Research: Mechanisms, processes and applications* (pp. 421-432). Amsterdam: North Holland.

Radach, R., & McConkie, G.W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), *Eye Guidance in Reading and Scene Perception* (pp.77-100). Oxford, UK: Elsevier.

Raney, G.E., & Rayner, K. (1995). Word frequency effects and eye movements during two readings of a text. *Canadian Journal of Experimental Psychology, 49,* 151-173.

Rayner, K. (1975a). Parafoveal identification during a fixation in reading. *Acta Psychologica, 39,* 271-282.

Rayner, K. (1975b). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65-81.

Rayner, K. (1979). Eye guidance in reading: fixation locations within words. *Perception, 8,* 21-30.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41,* 211-236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E.D. (2003). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z reader model. *(Under review)*

Rayner, K., Balota, D.A., & Pollatsek, A. (1986). Against parafoveal semantic preprocessing during eye fixations in reading. *Canadian Journal of Psychology, 40,* 473-483.

Rayner, K., & Bertera, J.H. (1979). Reading without a fovea. *Science, 206,* 468-469.

Rayner, K., Binder, K.S., Ashby, J., & Pollatsek, A. (2001). Eye movement control in reading: Word predictability has little influence on initial landing positions in words. *Vision Research, 41,* 943-954.

Rayner, K., & Duffy, S.A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity and lexical ambiguity. *Memory And Cognition, 14,* 191-201.

Rayner, K., & Fischer, M.H. (1996). Mindless reading revisited: Eye movements during reading and scanning are different. *Perception & Psychophysics, 58,* 734-747.

Rayner, K., Fischer, M.H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38,* 1129-1144.

Rayner, K., Inhoff, A.W., Morrison, R.E., Slowiaczek, M.L., & Bertera, J.H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 167-179.

Rayner, K., Kambe, G., & Duffy, S.A. (2000). The effect of clause wrap-up on eye movements during reading. *Quarterly Journal of Experimental Psychology, 53A,* 1061-1080.

Rayner, K., & McConkie, G.W. (1976). What guides a reader's eye movements? *Vision Research, 16,* 829-837.

Rayner, K., McConkie, G.W., & Ehrlich, S.F. (1978). Eye movements and integrating information across fixations. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 529-544.

Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye movements. *Cognitive Psychology, 12,* 206-226.

Rayner, K., & Morris, R.K. (1992). Eye movement control in reading: Evidence against semantic preprocessing. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 163-172.

Rayner, K., & Morrison, R.M. (1981). Eye movements and identifying words in parafoveal vision. *Bulletin of the Psychonomic Society, 17,* 135-138.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology, 33A,* 351-373.

Rayner, K., & Pollatsek, A. (1989). *The Psychology of Reading.* Englewood Cliffs, NJ: Prentice Hall.

Rayner, K., Pollatsek, A., & Binder, K. S. (1998). Phonological codes and eye movements in reading. *Journal of Experimental Psychology: Learning Memory and Cognition, 24,* 476-497.

Rayner, K., Reichle, E.D., & Pollatsek, A. (1998). Eye movement control in reading: An overview and model. In G. Underwood (Ed.), *Eye Guidance in reading and scene perception* (pp. 243-268). Oxford, UK: Elsevier.

Rayner, K., Sereno, S.C., & Raney, G.E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1188-1200.

Rayner, K., & Well, A.D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin and Review, 3,* 504-509.

Rayner, K., Well, A.D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. *Perception & Psychophysics, 27,* 537-544.

Rayner, K., Well, A.D., Pollatsek, A., & Bertera, J.H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31,* 537-550.

Rayner, K., White, S.J., Kambe, G., Miller, B., & Liversedge, S.P. (2003). On the processing of meaning from parafoveal vision during eye fixations in reading. In J. Hyönä, R. Radach, & H. Deubel (Eds). *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research* (pp. 213-234). Amsterdam: Elsevier.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105,* 125-157.

Reichle, E.D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: accounting for initial fixation locations and refixations within the E-Z reader model. *Vision Research, 39,* 4403-4411.

Reichle, E.D., Rayner, K., & Pollatsek, A. (in press). The E-Z Reader model of eye movement control in reading: Comparisons to other models. *Behavioural and Brain Sciences*

Reilly, R. (1993). A connectionist framework for modeling eye-movement control in reading. In G. d'Ydewalle, & J. Van Rensbergen, (Eds.), *Perception and Cognition: Advances in Eye Movement Research* (pp. 193-212.) Amsterdam: Elsevier.

Reilly, R.G., & O'Regan, J.K. (1998). Eye movement control during reading: A simulation of some word-targetting strategies. *Vision Research, 38,* 303-317.

Reilly, R.G., & Radach, R. (2003). Foundations of an interactive activation model of eye movement control in reading. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research* (pp.429-455). Amsterdam: Elsevier.

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia, 25,* 31-40.

Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research, 37,* 495-510.

Salvucci, D.D. (2001). An integrated model of eye movements and visual encoding. *Journal of Cognitive Systems Research, 1,* 201-220.

Schiepers, C. (1980). Response latency and accuracy in visual word recognition. *Perception & Psychophysics, 27,* 71-91.

Schroyens, W., Vitu, F., Brysbaert, M., & d'Ydewalle, G. (1999). Eye movement control during reading: foveal load and parafoveal processing. *Quarterly Journal of Experimental Psychology, 52A,* 1021-1046.

Schustack, M.W., Ehrlich, S.F., & Rayner, K. (1987). Local and global sources of contextual facilitation in reading. *Journal of Memory and Language, 26,* 322-340.

Shepherd, M., Findlay, J.M., & Hockey, R.J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology, 38A,* 475-491.

Shillcock, R., Ellison, T.M., & Monaghan, P. (2000). Eye-fixation behaviour, lexical storage and visual word recognition in a split processing model. *Psychological Review, 107,* 824-851.

Starr, M.S., & Inhoff, A.W. (in press). Attention Allocation to the Right and Left of a Fixated Word: Use of Orthographic Information from Multiple Words during Reading. *European Journal of Cognitive Psychology*

Stelmach, L.B., Campsall, J.M., & Herdman, C.M. (1997). Attentional and ocular movements. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 823-844.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donder's method. In W.G. Koster (Ed). *Acta Psychologica, 30, Attention and Performance II* (pp. 276-315). Amsterdam: North Holland.

Suppes, P. (1990). Eye-movement models for arithmetic and reading performance. In: E. Kowler (Ed.), *Eye Movments and Their Role in Visual and Cognitive Processes* (pp. 455-477). Amsterdam: Elsevier.

Suppes, P. (1994). Stochastic models of reading. In J. Ygge, & G. Lennerstrand (Eds.), *Eye movements in reading* (pp. 349-364). Oxford, UK: Pergamon Elsevier.

Thibadeau, R., Just, M.A., & Carpenter, P.A. (1982). A model of the time course and content of reading. *Cognitive Science, 6,* 157-203.

Tinker, M.A., & Paterson, D.G. (1939). Influence of type form on eye movements. *Journal of Experimental Psychology, 25,* 528-531.

Treisman A. M., Gelade G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97-136.

Tsai, J-L., & McConkie, G.W. (2003). Where do Chinese Readers Send Their Eyes? In J. Hyönä, J., R. Radach, & H. Deubel (Eds.), *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research* (pp. 159-176.). Amsterdam: Elsevier.

Underwood, G., Binns, A., & Walker, S. (2000). Attentional demands on the processing of neighbouring words. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 247-268). Oxford, UK: Elsevier.

Underwood, G., Bloomfield, R., & Clews, S. (1988).Information influences the pattern of eye fixations during sentence comprehension. *Perception, 17,* 267-278.

Underwood, G., Clews, S., & Everatt, J. (1990). How do readers know where to look next? Local information distributions influence eye fixations. *Quarterly Journal of Experimental Psychology, 42A,* 39-65.

Underwood, G., Hyona, J., & Niemi, P. (1987). Scanning patterns on individual words during the comprehension of sentences. In J.K. O'Regan & A. Lévy-Schoen (Eds.), *Eye movements: From physiology to cognition* (pp. 467-477). Amsterdam: Elsevier North Holland.

Vergilino, D., & Beauvillain, C. (2000). The planning of refixation saccades in reading. *Vision Research, 40,* 3527-3528.

Vergilino, D., & Beauvillain, C. (2001). Reference frames in reading: Evidence from visually guided and memory-guided saccades. *Vision Research, 41,* 3547-3557.

Vitu, F. (1991a). Against the existence of a range effect during reading. *Vision Research, 31,* 2009-2015.

Vitu, F. (1991b). The existence of a center of gravity effect during reading. *Vision Research, 31,* 1289-1313.

Vitu, F. (1991c). The influence of parafoveal preprocessing and linguistic context on the optimal landing position effect. *Perception & Psychophysics, 50,* 58-75.

Vitu, F., Brysbaert, M., & Lancelin, D. (in press). A test of parafoveal-on-foveal effects with pairs of orthographically related words. *European Journal of Cognitive Psychology*

Vitu, F., McConkie, G.W., Kerr, P., & O'Regan, J.K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research, 41,* 3513-3533.

Vitu, F., O'Regan, J.K., Inhoff, A.W., & Topolski, R. (1995). Mindless reading: Eye movement characteristics are similar in scanning letter strings and reading texts. *Perception & Psychophysics, 57,* 352-364.

Vitu, F., O'Regan, J.K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous texts. *Perception & Psychophysics, 47,* 583-600.

Vonk, W., Radach, R., & van Rijn, H. (2000). Eye guidance and the saliency of word beginnings in reading text In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 269-299). Oxford, UK: Elsevier.

Yang, S.-N., & McConkie, G.W. (2001). Eye movements during reading: A theory of saccade initiation time. *Vision Research, 41,* 3567-85.

Ygge, J., & Jacobson, C. (1994). Asymmetrical saccades in reading. In J. Ygge, & G. Lennerstrand (Eds.), *Eye movements in reading* (pp. 301-313). Oxford, UK: Pergamon Press.

Zola, D. (1984). Redundancy and word perception during reading. *Perception & Psychophysics, 36,* 277-284.

Appendices

Appendix A: Materials for Experiment 1

Experimental sentence frames and critical words for Experiment 1. The critical words are separated by slashes in the following order: Correct spelling / high frequency misspelling / low frequency misspelling / illegal pronounceable misspelling / illegal unpronounceable misspelling

The scientist worked in the large laboratory / liboratory / luboratory / lyboratory / lwboratory every day of the week.

The gallery presented great exhibitions / ethibitions / ephibitions / ebhibitions / dxhibitions during the school holidays.

Lipstick and blusher are costly cosmetics / casmetics / cysmetics / / cfsmetics bought by some women regularly.

The typist detested the quite loathsome / leathsome / llathsome / luathsome / lhathsome duties she was allocated each day.

The computer manual included modern technical / tachnical / tychnical / / tfchnical terms with no definitions.

Sometimes just a quick occasional / oncasional / oscasional / oacasional / tccasional phone call can reduce a parent's fears.

Power stations generate enough electricity / evectricity / edectricity / ekectricity / nlectricity every day for several towns.

Linguistics uses simple grammatical / glammatical / ghammatical / gwammatical / gfammatical rules to explain language structure.

The driving test demands rigid standards / shandards / skandards / srandards / sfandards before anyone can pass.

Statistics involves long boring analysis / awalysis / ajalysis / axalysis / tnalysis though some find it easy.

The jury reviewed fresh evidence / exidence / etidence / egidence / hvidence issued by the defence lawyer.

In the zoo the lively orangutan / okangutan / odangutan / omangutan / nrangutan swings from the ropes and bars.

Pollution threatened the entire ecological / enological / ebological / edological / hcological system including many rare plants.

The religion adopted a strong ideology / ineology / ibeology / ijeology / hdeology linked to biblical scriptures.

At the party Jim drank superb champagne / clampagne / cyampagne / / cnampagne until there was none left.

Maths is taught using simple arithmetic / alithmetic / akithmetic / ayithmetic / xrithmetic tests in many schools.

The students liked the modern university / usiversity / ubiversity / ufiversity / dniversity flats as much as living at home.

In the shop the young assistant / absistant / aisistant / avsistant / wssistant tried to help the difficult customer.

There will always be small variation / veriation / voriation / vuriation / vhriation within each individual's responses.

The campaign attacks the entire abortion / anortion / aeortion / akortion / wbortion issue including embryo research.

Dinosaurs underwent total extinction / entinction / eutinction / ebtinction / cxtinction before humans evolved.

Teachers dislike the modern education / equcation / ecucation / etucation / fducation system because it is so inflexible.

The picture book had colour illustrations / islustrations / iglustrations / ijlustrations / hllustrations after each paragraph.

Before the elections the honest politicians / puliticians / pyliticians / / pnliticians tried to listen to the voters.

Bill relaxed in the superb comfortable / camfortable / cymfortable / / cnmfortable chair at the end of the hard day.

Farmers complained when local agricultural / acricultural / aoricultural / akricultural / ngricultural ground was contaminated.

The cartoon was the latest animation / abimation / azimation / ajimation / wnimation aimed at educating children.

When the other ideas failed a better alternative / auternative / aeternative / avternative / nlternative theory was suggested.

Good essays are given truly excellent / encellent / eucellent / epcellent / bxcellent marks if they include strong arguments.

The ugly sculptures looked oddly grotesque / glotesque / gnotesque / gwotesque / gfotesque after the paint had dried.

The receipt ensured a total guarantee / grarantee / gnarantee / gwarantee / gparantee except for water damage.

The extra revision for the first examination / enamination / egamination / ekamination / txamination paper had been beneficial.

The novelist loved to study modern literature / laterature / luterature / lyterature / lhterature after work in the evenings.

The entertainment provided great amusement / adusement / avusement / axusement / tmusement before the fire alarm sounded.

It was hopeless but the young desperate / disperate / dysperate / dwsperate / dnsperate woman prayed all night.

Appendix B: Materials for Experiment 2

Experimental sentence frames and critical words for Experiment 2. The critical words are separated by slashes in the following order: Correct spelling / M2UP4 / M2UP5 / M4UP4 / M5UP5

The experts watched the young amateurs / acateurs / anateurs / amareurs / amatiurs trying to solve the puzzle.

The chemist conducted a formal analysis / awalysis / amalysis / anadysis / analtsis every twenty minutes.

The singer received lively applause / asplause / amplause / apphause / applouse after the excellent performance.

The troops waited for the heavy artillery / aftillery / antillery / artallery / artirlery until the sergeant sent new orders.

The villain tried to contact the secret associate / ansociate / absociate / assyciate / assomiate before the police found him.

The students used telescopes in the basic astronomy / antronomy / attronomy / astlonomy / astrenomy course every Thursday.

The headmaster calculated the class averages / agerages / amerages / avesages / averiges before the staff meeting.

The police told the residents about the recent burglary / borglary / barglary / burclary / burgrary crimes in the area.

She checked the date on the pretty calendar / culendar / celendar / caldndar / calerdar before confirming the appointment.

The builder wished that the young carpenter / cerpenter / corpenter / carhenter / carpanter would agree to help with the job.

The butler asked the honest chauffeur / crauffeur / clauffeur / chakffeur / chaunfeur about the stolen car.

The moon formed a clear crescent / clescent / chescent / crelcent / creshent shape high in the sky.

The musicians waited for the great conductor / cenductor / canductor / conhuctor / condactor before the concert began.

The new houses were built opposite the pretty cottages / cittages / cuttages / cotlages / cotteges behind the church.

The secretary took pride in her quick dictation / dectation / doctation / diclation / dictotion until she made a big mistake.

The giant footprints were made when large dinosaurs / danosaurs / denosaurs / dinusaurs / dinocaurs lived on the earth.

The publisher decided to launch the recent editions / evitions / epitions / edinions / edituons before Christmas.

The fire brigade always evacuate / elacuate / exacuate / evatuate / evaciate hotels even if they suspect a false alarm.

The businesswoman told the junior executive / evecutive / elecutive / exesutive / execitive about the new deal.

The police said that despite the major emergency / elergency / exergency / emelgency / emercency people should remain calm.

The bank manager offered annual financial / funancial / fanancial / finoncial / finascial advice to his regular customers.

The personnel officer knew that the boss often harassed / horassed / herassed / harossed / hararsed staff about deadlines.

Once the hostages were released the proud mediator / madiator / modiator / medeator / medintor wrote about the experience.

The estate agent asked if the large mortgage / mertgage / martgage / morugage / mortrage could be transferred.

The geologist studied common minerals / menerals / monerals / minprals / minewals found in the Kenyan mountains.

The protestors organised a small petition / putition / pitition / petotion / petision about the building of the new road.

In the laboratory a large / practical phactical / plactical / praltical / prachical class was working on a new project.

The group has many aims but the major purposes / parposes / perposes / purnoses / purpeses should take priority.

The staff timetable was organised in strict rotation / ratation / retation / rothtion / rotagion during each semester.

The abandoned seal was taken to the quiet sanctuary / senctuary / sinctuary / sanytuary / sanotuary whilst he recovered.

Jenny doubted Phil's story but she was often sceptical / speptical / steptical / scertical / sceppical about such rumours.

The body builders took strong steroids / sleroids / sheroids / stesoids / steraids until new regulations were established.

The nuns sang quiet spiritual / sliritual / shiritual / spisitual / spirotual hymns whilst the bishops were ordained.

There was a huge storm and Tom was truly saturated / seturated / siturated / satorated / satusated during the downpour.

Lots of money was raised from the recent sponsored / slonsored / stonsored / spomsored / sponfored events for local charities.

Italian food often includes thick spaghetti / smaghetti / staghetti / spalhetti / spagnetti along with a delicious sauce.

The surgeon asked for some clean scalpels / spalpels / smalpels / scaspels / scalrels before he made the incision.

In his review Jim was asked to mainly summarize / sommarize / simmarize / sumbarize / summurize recent changes to the company.

Sandra's jewellery was quite valuable / viluable / voluable / valtable / valumble except for a couple of worthless rings.

The horizontal rows crossed the narrow vertical / vartical / virtical / verlical / vertacal column on the spreadsheet.

Appendix C: Materials for Experiment 3

Experimental sentences and critical string for each condition in Experiment 3. The slashes denote the correctly spelled condition, the uninformative misspelled condition and the informative misspelled condition respectively.

Derek is usually very busy but he is mostly available / anailable / acailable today and tomorrow.

The error was not major but the small omission / orission / opission would be noticed.

The cartoon was the latest animation / alimation / abimation aimed at educating children.

Smokers have a higher nicotine / necotine / nucotine intake than non-smokers.

John liked pears but he hated green avocados / abocados / arocados unless they were oven baked.

The funding cuts started with a sharp reduction / raduction / roduction before a more gradual decline.

The musicians enjoyed playing in the small orchestra / occhestra / onchestra every Monday night.

Sophie was a daydreamer and she often imagined / inagined / itagined being in her own fantasy world.

The university had a strict admission / armission / atmission policy for recruiting the top students.

Gas and electricity are basic utilities / unilities / usilities across the Western world.

Anna felt guilty and decided to calmly apologize / adologize / alologize before she was found out.

The beaches change shape as the sea deposits small sediment / sadiment / sudiment during high tides.

Kim was delighted with the simply wonderful / winderful / wenderful sweets and birthday card.

The religious man prayed for his sacred saviours / seviours / soviours every night before bed.

The sandpaper had a rough abrasive / arrasive / aprasive finish for very coarse sanding.

Dave thought it was absurd that the modern ludicrous / ladicrous / ledicrous ideas were applied.

Pip hated stairs and he even used the short escalator / encalator / eacalator down to the first floor.

The gas cooker required a quick ignition / innition / isnition before the oven lighted.

The polished glass had a really brilliant / blilliant / beilliant shine after the spring clean.

The builder gave a cheap estimate / entimate / eitimate before he realised the tiles were expensive.

The distillation process produced clean extracts / estracts / eatracts during the second stage.

The nature of our future humanity / homanity / himanity relies on maintaining our civil rights.

Linda was in debt and soon the nasty bailiffs / briliffs / boiliffs would possess the flat.

The doctor prescribed drugs for the strong abdominal / audominal / aidominal pains despite the risks.

Appendix D: Materials for Experiments 4 and 5

Experimental sentence frames and critical words in Experiments 4 and 5. The critical words are underlined. For each sentence frame, version a. is the irregular beginning word condition and version b. is the regular beginning word condition.

1a. He knew that the clever <u>auctioneer</u> would ask him about the valuable lots.
1b. He knew that the clever <u>candidates</u> would produce impressive answers.
2a. Last Friday the modern <u>ergonomic</u> chairs were transported to the shops.
2b. Last Friday the modern <u>miniature</u> chairs were placed in the dolls house.
3a. It is true that the daily <u>oestrogen</u> level varied but it was not harmful.
3b. It is true that the daily <u>infection</u> level increased over the critical period.
4a. Eventually the funny <u>ostriches</u> walked over to the fence near the visitors.
4b. Eventually the funny <u>foreigner</u> walked over to the bar to tell his new joke.
5a. He would need some strong <u>ammunition</u> before taking the troops into battle.
5b. He would need some strong <u>explosives</u> before the rocks could be removed.
6a. He read the recent <u>veterinary</u> report before he made his recommendations.
6b. He read the recent <u>assessment</u> report before he decided on the changes.
7a. She knew that the recent <u>fumigation</u> effort had been a success.
7b. She knew that the recent <u>inspection</u> effort had helped to improve food hygiene.
8a. It is difficult to truly <u>jeopardize</u> talks because no one ever listens.
8b. It is difficult to truly <u>transcribe</u> talks when there is background noise.
9a. On Tuesday the young <u>rhinoceros</u> would need her first injections.
9b. On Tuesday the young <u>management</u> would be asked to outline the new plans.
10a. Suddenly the angry <u>usherette</u> rushed up the aisle to the noisy children.
10b. Suddenly the angry <u>alligator</u> rushed towards the small canoe.
11a. He knew that he could easily <u>eradicate</u> houses that were infested with mice.
11b. He knew that he could easily <u>entertain</u> houses full of guests.
12a. She knew that the modern <u>ointments</u> would work if she could get them in time.
12b. She knew that the modern <u>extension</u> would add value to the house.
13a. He took the usual <u>eucalyptus</u> after his other medication.
13b. He took the usual <u>supplement</u> after he considered changing to the new one.
14a. He was mainly <u>omnivorous</u> during the summer season.

14b. He was mainly monotonous during the long lectures.

15a. He said that three emulsions could be used to paint the old house.

15b. He said that three accidents could have been prevented.

16a. He used a clever pseudonym trick to deceive the authorities.

16b. He used a clever plausible trick to avoid embarrassment over the mistake.

17a. Finally the major nunneries became very busy as tourists began to visit them.

17b. Finally the major statement became available and was issued to the employees.

18a. Often the quiet lullabies would send the babies to sleep.

18b. Often the quiet spectator would read a book or listen to a personal stereo.

19a. They asked about the small cemeteries after the rumours about the closures.

19b. They asked about the small challenges after the group completed the report.

20a. She asked about the social etiquette during the important dinner party.

20b. She asked about the social programme during the Christmas celebrations.

21a. He hated the heavy pneumatic tools that were used to dig up the road.

21b. He hated the heavy primitive tools that the farmer gave him to use.

22a. The trainees used the usual mnemonics until they understood the new material.

22b. The trainees used the usual treatment until their wounds had healed.

23a. Yesterday the three agnostics asked each other about the meaning of life.

23b. Yesterday the three graduates asked about the new employment scheme.

24a. Eventually the young fugitives asked if they could have some food.

24b. Eventually the young designers asked if they could have a pay rise.

Appendix E: Materials for Experiments 6 and 7

Experimental sentences and critical string for each condition in Experiment 6. The slashes denote the high and low frequency word n-1 respectively. The misspelled critical string is shown in brackets. The sentences in italics are those which were presented in Experiment 7. If only one version of each sentence is listed then the same sentence was presented in both Experiments 6 and 7.

The prosecution decided to call the final / dowdy witnesses (wytnesses) after the jury returned. *The prosecution decided to call the final / naive witnesses (wytnesses) after the jury returned.*

The students talked to the recent / smarmy graduates (gwaduates) after the company presentation. *The students talked to the recent / genial graduates (gwaduates) after the company presentation.*

Before the important concert the bright / dainty musicians (mbsicians) asked for new instruments.

The tax forms were complicated and the local / inept accountant (ajcountant) tried to help. *The tax forms were complicated and the local / inept accountant (ajcountant) could not work them out.*

The employees hoped that the pretty / scatty assistant (aqsistant) would be fired. *The employees hoped that the pretty / candid assistant (aqsistant) would be fired.*

High up on the hills the angry / gruff shepherds (sbepherds) looked for the lost sheep. *High up on the hills the angry / burly shepherds (sbepherds) looked for the lost sheep.*

The hungry boy knew that the useful / mouldy groceries (gdoceries) would have to be eaten. *The hungry boy knew that the heavy / moldy groceries (gdoceries) would have to be eaten.*

They hoped that the holiday would be a social / scenic experience (ekperience) after the hard work. *They hoped that the vacation would be a social / scenic experience (ekperience) after the hard work.*

Before the election the awful / terse councillor (cwuncillor) issued a leaflet about his policies. *Before the election the awful / terse councilor (cwuncilor) issued a leaflet about his policies.*

The tourists enjoyed talking to the young / agile traveller (tlaveller) about his many experiences. *The tourists enjoyed talking to the young / agile travelers (tlavelers) about their big adventure.*

The travel guide asked the single / chirpy foreigner (fsreigner) about his journey home. *The travel guide asked the single / fluent foreigner (fsreigner) about his journey home.*

The administrator was annoyed when the public / bolshy officials (oyficials) named the employees. *The administrator was annoyed when the public / docile officials (oyficials) named the employees.*

The brave explorers knew that the great / fated endeavour (ezdeavour) would need a lot of effort. *The brave explorers knew that the great / fated endeavors (ezdeavors) would need a lot of effort.*

The corporal guarded the united / peeved militants (mhlitants) until they were released.

The group knew that the entire / scanty discussion (dwscussion) would be essential for the decision.

The outdoor centre organised the usual / cushy activities (axtivities) inside when it rained. *The outdoor center organised the usual / cushy activities (axtivities) inside when it rained.*

The office staff were surprised when the lucky / dotty secretary (sfcretary) found a new job. *The office staff were surprised when the lucky / timid secretary (sfcretary) found a new job.*

The university officers asked the gentle / sedate chancellor (cdancellor) about the opening ceremony.

Jen worried about her short / obese appearance (azpearance) though really she looked beautiful.

The depressive man visited his normal / jovial therapist (tnerapist) daily during the winter. *The depressed man visited his normal / jovial therapist (tnerapist) daily during the winter.*

The government insisted that the senior / risque politician (pflitician) never intended to offend.

The passengers waited for the civil / inane conductor (cjnductor) before they got on the bus. *The passengers waited for the civil / frail conductor (cjnductor) before they got on the bus.*

The neighbours were anxious about the happy / bossy strangers (sgrangers) moving in next door. *The neighbors were anxious about the happy / bossy strangers (sgrangers) moving in next door.*

The camera crew waited for the quick / livid reporters (ryporters) before they broadcast the news. *The camera crew waited for the quick / rival reporters (ryporters) before they broadcast the news.*

The soldiers admired the tough / famed sergeants (sjergents) during the tense conflict.

The women struggled with the major / taboo campaigns (cgmpaigns) until their fight was over.

The pupils were glad that the proud / podgy principal (pnincipal) wished to improve the school. *The pupils were glad that the honest / senile principal (pnincipal) wanted to retire early.*

The food was always delicious at the little / swanky restaurant (rhstaurant) behind the old church.

At the meeting the whole / rowdy committee (ctmmittee) voted against the planning application.

The students disliked the sharp / wispy professor (pkofessor) though they knew he was very clever. *The students disliked the sharp / lofty professor (pkofessor) though they knew he was very clever.*

The train spotters knew that the quiet / perky enthusiast (ebthusiast) wanted to ride with the driver. *The hikers knew that the quiet / perky enthusiast (ebthusiast) wanted to climb the big mountain.*

The driver asked about the simple / odious insurance (ibsurance) before he bought the new car.

People were suspicious of the silent / smutty individual (ikdividual) though no one would admit it. *People were suspicious of the silent / snazzy individual (ikdividual) though no one would admit it.*

The politicians demanded that the guilty / stingy ministers (mtnisters) should resign immediately.

After the plane crash the secret / tetchy survivors (sdrvivors) walked to the end of the island. *After the plane crash the secret / devout survivors (sdrvivors) walked to the end of the island.*

The bank manager asked about the right / nifty investment (ijvestment) before he made a decision.

The surgeon asked about the proper / shoddy operation (ogeration) before the hospital enquiry. *The surgeon asked about the modern / shoddy operation (ogeration) before the hospital enquiry.*

The journalists received the clear / brash statement (sratement) before the newspaper deadline. *The journalists received the clear / nobel statement (sratement) before the newspaper deadline.*

In the expensive hotel the royal / lanky attendant (aktendant) helped carry the luggage.

The employees were angry because the upper / irate management (mcnagement) wanted redundancies.

The wedding guests enjoyed the small / swish reception (rsception) after the ceremony. *The wedding guests enjoyed the lovely / lavish reception (rsception) after the ceremony.*

The workers arranged a meeting with their formal / fickle superiors (szperiors) about the pay rise.

The timber was very heavy and the strong / frugal carpenter (cmrpenter) asked for help.

The biologist explained that the female / crafty parasites (pcrasites) never kill their hosts.

The interviewer asked the likely / uppity candidate (cbndidate) about his qualifications.

The workers arranged a party for their tired / suave colleague (cslleague) before he retired.

The civil servants told the future / snooty president (pgesident) about the country's problems.

After the circus act the famous / nimble performer (pwrformer) stood to receive the applause.